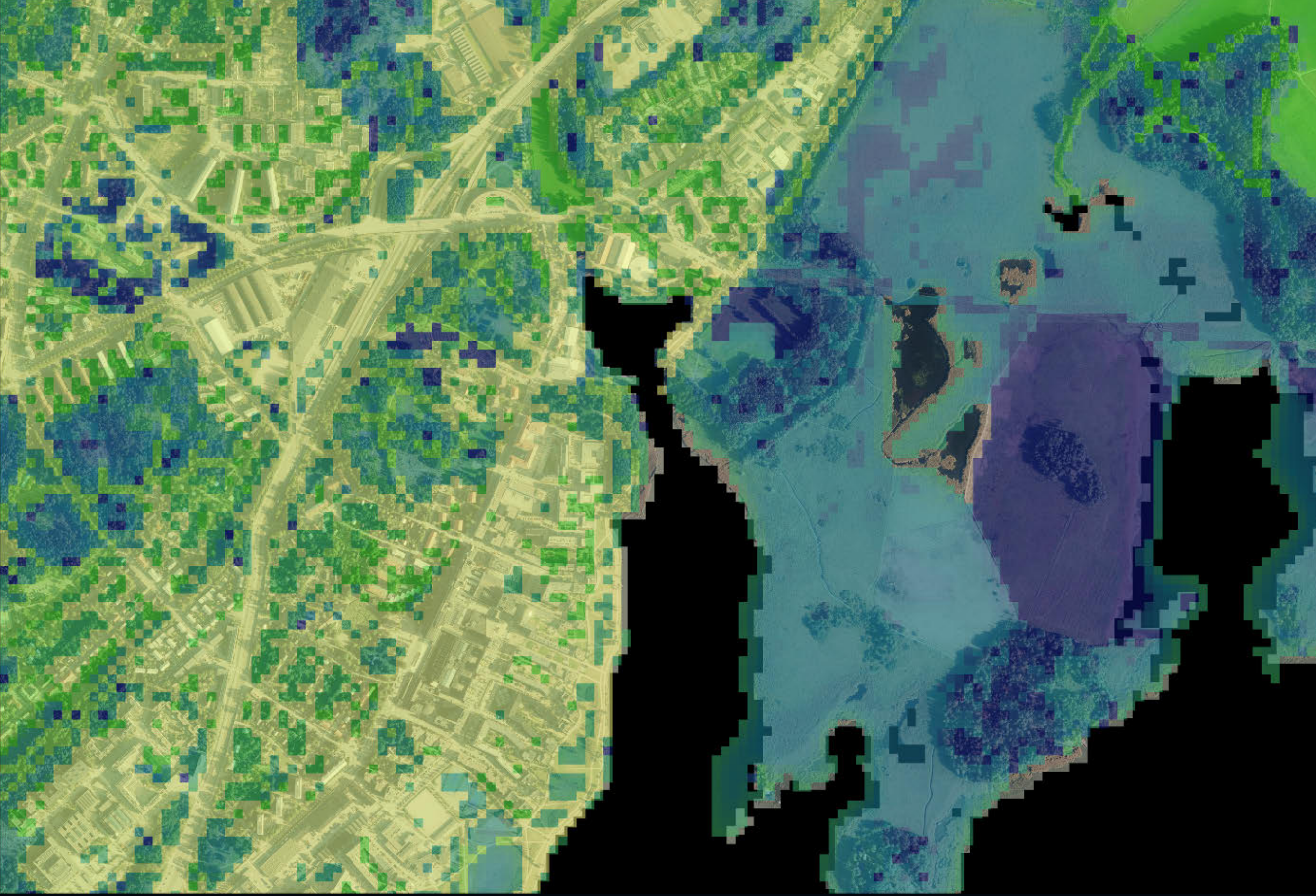

DEPARTMENT OF GEOSCIENCES AND GEOGRAPHY A88

Spatial Conservation Prioritization for the Benefit of Urban and Regional Land-use Planning

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UNIVERSITY OF HELSINKI
FACULTY OF SCIENCE

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ACADEMIC DISSERTATION
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“They had passed into Nan Curunír, the Wizard's Vale. -- Once it had been fair and green, and through it the Isen flowed, already deep and strong before it found the plains; for it was fed by many springs and lesser streams among the rain-washed hills, and all about it there had lain a pleasant, fertile land.

“It was not so now. Beneath the walls of Isengard there still were acres tilled by the slaves of Saruman; but most of the valley had become a wilderness of weeds and thorns. Brambles trailed upon the ground, or clambering over bush and bank, made shaggy caves where small beasts housed. No trees grew there; but among the rank grasses could still be seen the burned and axe-hewn stumps of ancient groves. It was a sad country, silent now but for the stony noise of quick waters. --

“Beneath the mountain's arm within the Wizard's Vale through years uncounted had stood that ancient place that Men called Isengard. Partly it was shaped in the making of the mountains, but mighty works the Men of Westernesse had wrought there of old; and Saruman had dwelt there long and had not been idle. --

“Once it had been green and filled with avenues, and groves of fruitful trees, watered by streams that flowed from the mountains to a lake. But no green thing grew there in the latter days of Saruman. The roads were paved with stone-flags, dark and hard; and beside their borders instead of trees there marched long lines of pillars, some of marble, some of copper and of iron, joined by heavy chains. --

“The plain, too, was bored and delved. Shafts were driven deep into the ground; their upper ends were covered by low mounds and domes of stone, so that in the moonlight the Ring of Isengard looked like a graveyard of unquiet dead. For the ground trembled. The shafts ran down by many slopes and spiral stairs to caverns far under; there Saruman had treasuries, store-houses, armouries, smithies, and great furnaces. Iron wheels revolved there endlessly, and hammers thudded. At night plumes of vapour steamed from the vents, lit from beneath with red light, or blue, or venomous green.”

J. R. R. Tolkien. The Lord of the Rings: Two Towers.
2020 Hardback edition, HarperCollinsPublishers, London

Jalkanen J., 2020. *Spatial conservation prioritization for the benefit of urban and regional land-use planning*. Department of Geosciences and Geography A88. 64 pages and 7 figures.

ABSTRACT

In a world of alarmingly rapid biodiversity decline and increasing urban expansion, as well as other land use pressures, the need for ecologically aware land-use planning is self-evident. In addition, especially in urban areas, land-use planners need to acknowledge that the same areas hold value for both nature and people, but possibly with contrasting patterns. How to ensure that land-use planning systematically accounts for ecological and social requirements is a great challenge for land-use planners throughout the world.

Spatial (conservation) prioritization is about the identification of priority areas for conservation in a systematic and efficient way. In the past two decades, spatial prioritization has become commonly used in conservation planning and it has been utilized in different environments in many parts of the world. However, spatial prioritizations have been less commonly incorporated in an urban context or as an integral part of the general land-use planning process.

In my thesis, I demonstrate how to use spatial prioritization, more specifically the Zonation software, in a way that delivers useful information for regional and urban land-use planners. The thesis consists of a summary and four chapters. In **I**, I show how urban biodiversity can be understood in urban spatial prioritizations. In **II**, I demonstrate how spatial prioritization can be used to identify the most important urban green areas based on socially equitable accessibility. In **III**, I discuss experiences from the planning case of the Uusimaa region (South-Finland), where Zonation was used to provide information about biodiversity values specifically for the purpose of regional zoning. I introduce a workflow for using prioritization in general land-use planning. Finally, in **IV**, I identify regional-level ecological networks and corridors with Zonation in an evaluation of a proposed long-term regional plan.

My thesis demonstrates that the need for balancing many land-use interests simultaneously distinguishes the context of land-use planning from academic research or conservation planning. In the context of land-use planning, the use of diverse high-quality biodiversity data is a definite requirement. In Finland, systematic collection of biodiversity data should be continued and expanded, and the accessibility of the data from different institutions should be improved to facilitate ecologically well-informed land-use planning. Furthermore, to ensure that the priority areas make their way into the land-use plans, it is vital to carefully consider how prioritization is integrated into the general zoning process. Ecological connectivity is an important but difficult topic in land-use plan-

ning, and ways to account for it in zoning maps should be developed. Connectivity is typically emphasized by identifying linear-type ecological corridors in target landscapes, which, according to my thesis, should be restricted for showing narrow connectivity bottlenecks in the landscape. In general, a zone-type connectivity symbol should be preferred over linear-type corridor symbols.

Spatial prioritization aims at cost-efficient results which may make it appealing for growing and densifying cities. As shown by my thesis, the objectives of urban spatial prioritization analyses must be set carefully, and the data used must reflect those objectives. For instance, how urban biodiversity is measured in spatial prioritizations must be carefully considered if the results are intended to be compatible with the concept of multifunctional and resilient urban green infrastructure. In cities, the human dimension of green areas cannot, and should not, be excluded, and the perspective of social equitability should be addressed as well.

To conclude, general land-use planning benefits from spatial prioritization that allows a great amount of relevant ecological (and other types of) data to be synthetized into a spatially explicit form. Prioritization results, such as priority maps produced by Zonation, are however not plans *per se*, but inputs to and facilitators of land-use planning that can effectively avoid the harmful impacts to biodiversity. Spatial prioritization still has great, underutilized potential to support ecologically and socially sustainable land-use planning.

TIIVISTELMÄ

Luonnon monimuotoisuus hupenee kaupunkien laajenemisen ja muiden maankäyttöpaineiden vuoksi hälyttävää tahtia, mikä korostaa ekologisesti informoidun maankäytön suunnittelun tarvetta. Erityisesti kaupungeissa eri alueet voivat olla merkityksellisiä niin luonnon kuin ihmisten näkökulmasta, mutta eri tarpeet voivat olla ristiriidassa keskenään. Maankäytön suunnittelun suurimpia haasteita onkin se, miten ekologiset ja sosiaaliset tarpeet saadaan huomioitua systemaattisesti osana suunnittelua.

Spatiaalinen (suojelu-) priorisointi on menetelmä, jonka avulla voidaan tunnistaa arvokkaimpia alueita systemaattisesti ja kustannustehokkaan suojelun näkökulmasta. Spatiaalinen priorisointi on otettu laajalti käyttöön suojelusuunnittelun tueksi eri puolilla maailmaa ja hyvin erilaisissa suunnittelutilanteissa viimeisen reilun 20 vuoden aikana. Spatiaalista priorisointia ei ole kuitenkaan juuri hyödynnetty kaupunkiseuduilla tai osana yleistä maankäytön suunnittelua.

Osoitan väitöskirjassani erilaisten tapaustutkimusten avulla, kuinka spatiaalinen priorisointi ja erityisesti Zonation-tietokoneohjelma voi tuottaa kaupunki- ja maakuntatason maankäytön suunnittelua tukevaa tietoa. Väitöskirjani koostuu johdannosta ja neljästä osatyöstä. Osatyössä **I** tutkin, miten kaupunkiluonnon monimuotoisuutta tulisi tarkastella priorisointi-analyyseissä. Osatyössä **II** käytän spatiaalista priorisointia tunnistaakseni kaupungin tärkeimmät viheralueet tasa-arvoisen saavutettavuuden kannalta. Osatyö **III** käsittelee kokemuksia Zonationin käytöstä osana Uudenmaan maakuntakaavoitusta ja siitä, miten spatiaalinen priorisointi tulisi nivoa osaksi kaavoitusprosesseja. **IV**-osatyössä tunnistan Zonationin avulla laajoja ekologisia verkostoja ja yhteyksiä maakunnan mittakaavassa.

Kuten väitöskirjani osoittaa, maankäytön suunnittelun konteksti eroaa spatiaalisen priorisoinnin kannalta esimerkiksi luonnonsuojelusuunnittelusta tai tutkimuksesta, sillä maankäytön suunnittelun tulee pystyä vastaamaan samanaikaisesti ja tasapuolisesti hyvin erilaisiin maankäytön vaatimuksiin. Maankäytön suunnittelun kontekstissa monipuolisen ja laadukkaan luontotiedon käyttäminen on priorisointien ehdoton vaatimus. Suomessa tulee kerätä systemaattisesti ja kattavasti luontotietoa, ja aineistojen tulisi olla käytettävissä suunnitteluun. Jotta spatiaalinen priorisointi todella vaikuttaisi maankäytön suunnitteluun, priorisointi tulisi sisällyttää huolellisesti osaksi maankäytön suunnitteluprosessia. Ekologinen kytkeytyvyys on tärkeä, joskin vaikea aihe maankäytön suunnittelussa, ja kaavoituksen tulisi pystyä turvaamaan kytkeytyvyys nykyistä paremmin. Kytkeytyvyys huomi-

oidaan yleensä erilaisin viivamaisin yhteysmerkinnöin, jotka tulisi tutkimukseni perusteella rajata kapeiden pullonkaulakohtien esittämiseen. Erilaiset aluemerkinnät olisivat yleisesti viivamaisia merkintöjä perustellumpia kytkeytyvyyden näkökulmasta.

Spatiaalinen priorisointi tuottaa kustannustehokkaita ratkaisuja, mikä tekee siitä mielekkään työkalun kasvavien ja tiivistyvien kaupunkien suunnitteluun. Kuten väitöskirjassani kuvaan, kaupunkialueiden priorisointianalyysien tavoitteet täytyy kuitenkin suunnitella huolellisesti ja käytettävien lähtöaineistojen tulee olla yhteensopivia tavoitteiden kanssa. Esimerkiksi se, miten kaupunkiluonnon monimuotoisuus käsitetään ja miten sitä mitataan monitoiminnallisen ja kestävän viherrakenteen osana tulee suunnitella huolellisesti. Kaupungeissa ihmisnäkökulmaa ei voi jättää huomiotta, ja sosiaalinen yhdenvertaisuus tulee muistaa myös spatiaalisissa priorisoinneissa.

Spatiaalinen suojelupriorisointi voi siis hyödyttää maankäytön suunnittelua, sillä priorisointi muodostaa spatiaalisesti tarkan synteesin valtavasta määrästä luonto- ym. aineistoja. Priorisoinnin tulokset, kuten Zonation-ohjelman prioriteettikartat, eivät kuitenkaan tuota lopullista ratkaisua maankäytöstä, vaan auttavat suunnittelijoita löytämään ekologisesti ja sosiaalisesti kestäviä maankäytön ratkaisuja. Spatiaalisella suojelupriorisoinnilla on vielä paljon annettavaa kestävän maankäytön suunnittelun tueksi.

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications, which are referred to in the text by their roman numerals:

I **Jalkanen J**, Vierikko K, Moilanen A (2020) Spatial prioritization for urban Biodiversity Quality using biotope maps and expert opinion. *Urban Forestry & Urban Greening* 49: 126586. doi:10.1016/j.ufug.2020.126586

II **Jalkanen J**, Fabritius H, Vierikko K, Moilanen A, Toivonen T (2020) Analyzing fair access to urban green areas using multimodal accessibility measures and spatial prioritization. *Applied Geography* 124: 102320. doi:10.1016/j.apgeog.2020.102320

III Toivonen T, Kuusterä J, **Jalkanen J**, Kukkala A, Lehtomäki J, Aalto S, Moilanen A. Spatial conservation prioritisation as part of a general land use planning process. *Submitted manuscript*

IV **Jalkanen J**, Toivonen T, Moilanen A (2020) Identification of ecological networks for land-use planning with spatial conservation prioritization. *Landscape Ecology* 35: 353–371. doi:10.1007/s10980-019-00950-4

Table of contributions

	I	II	III	IV
Original idea	JJ, KV, AM	JJ	AM, TT, SA	AM, TT
Study design	JJ, AM	JJ, HF, TT, AM, KV	AM, TT, JK, SA	AM, TT, JJ
Data	JJ, KV	HF, JJ	JK, JJ	JJ
Analyses	JJ, AM	JJ, HF	JK, JJ	JJ
Manuscript preparation	JJ, AM, KV	JJ, TT, KV, AM, HF	TT, JJ, AK, JL, AM, SA	JJ, AM, TT

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TT: Tuuli Toivonen

1. INTRODUCTION

People are transforming the biosphere and causing a rapid loss of biodiversity (Butchart et al. 2010; Steffen et al. 2015). Unsustainable land-use is the biggest driver of the current biodiversity crisis (Joppa and Pfaff 2009; Newbold et al. 2015, 2016; IPBES 2019a). One type of contemporary land-use change that threatens biodiversity is urbanization, as expanding and densifying cities spread into natural and seminatural lands around and inside urban borders (Marzluff 2002; Ricketts and Imhoff 2003; Dearborn and Kark 2010; Seto et al. 2012; Soanes et al. 2018).

At the same time, the importance of urban green areas and biodiversity to peoples' well-being in urban areas has become widely acknowledged (Tzoulas et al. 2007; Dearborn and Kark 2010; Bertram and Rehdanz 2015; Carrus et al. 2015; Parajuli et al. 2018). Different types of urban green areas provide ecosystem services that benefit urban people (Gaston et al. 2013; Haase et al. 2014; Derkzen et al. 2015; Woodruff and Bendor 2016) and can harbor surprisingly high biodiversity (Niemelä 1999a, b; Brandl et al. 2004; Kowarik 2011). The role of biodiversity and provision of ecosystem services for people is, of course, not limited to urban areas (Kremen 2005; Jones-Walters 2008; Burkhard et al. 2013; Newbold et al. 2015; Grêt-Regamey et al. 2017; Kremen and Merenlender 2018).

Land-use planning is, essentially, the spatial coordination of human actions and interests in space (Theobald et al. 2000; Albrechts 2012). The current degradation of ecosystems calls for well-functioning and well-informed land-use planning in both urban and rural areas, and at multiple spatial scales (EU Science for Environment Policy 2016; IPBES 2019b). Accounting for ecology in land-use planning is often hindered by the lack of adequate ecological data. However, in places where there is comparatively good access to ecological data, such as in northern Europe, land-use planning can become complicated due to the *amount* of data. Fully accounting for hundreds of data layers describing species and habitats can easily become an overwhelming task. Furthermore, because land is a limited resource, choices and compromises are inescapable. In cities, for example, biodiversity conservation competes with other desirable goals such as sufficient housing for people or urban structure that supports low-carbon transport systems. Therefore, land-use planning would benefit from cost-efficient methods which account for ecological information.

To improve the quality of nature conservation planning in a world of ever-limited resources and competing interests, spatial (conservation) prioritization emerged in the late 1990s (Margules and Pressey 2000; Sarkar and Illoldi-Range 2010; Kukkala and Moilanen 2013; Sinclair et al. 2018). Spatial prioritization is about identifying optimal locations for conservation actions, such as establishing new protected areas or directing urban expansion so that biodiversity would have minimal negative impacts. Spatial prioritization typically operates with a large amount of spatial ecological data (about e.g. species or ecosystem services) and provides cost-efficient results in which all input features are represented in a balanced manner (Margules and Pressey 2000; Kukkala and

Moilanen 2013; Kullberg et al. 2015; Veach et al. 2017). Spatial prioritization can also account for different limitations of conservation such as costs, landowners' willingness for conservation, and connectivity and other ecological elements. Spatial prioritization is currently widely used in conservation planning throughout the world (Sinclair et al. 2018) and has been also adopted for general land-use planning in some areas, especially in South Africa (Botts et al. 2019).

In this thesis, I explore the utility of spatial prioritization for general land-use planning. More specifically, my objectives are:

1. To understand how the operational context of land-use planning differs from the context of conservation research when doing spatial prioritization
2. To demonstrate and elaborate upon how spatial prioritization could be utilized in urban areas
3. To understand the potential of spatial prioritization to support general land-use planning

I emphasize that although this thesis relates to land-use planning, planning itself was not the topic of this work. Land-use planning is a complex web of sociopolitical and institutional systems and a broad field of research itself. Instead, I focus on spatial prioritization but in the light of general land-use planning rather than from the perspective of more traditional conservation planning applications.

1.1. BIODIVERSITY AND CITIES

Cities are areas of high biodiversity (Niemelä 1999b; Brandl et al. 2004; Kowarik 2011; Soanes et al. 2018) and, being concentrated areas of people, are hotspots of socioecological systems (Andersson et al. 2014; Meerow et al. 2016; Korpilo et al. 2018; Vierikko et al. 2020). Cities are typically established on areas of high natural biodiversity: high fertility, varying topography, and near water (Brandl et al. 2004). Furthermore, cities are characterized by very diverse disturbance patterns and small-scale mosaics of different habitat types (Cadenasso et al. 2007). People have also introduced many species to cities around the world, both intentionally and by accident (McKinney 2002; Kowarik 2011). These last examples describe well how urban ecosystems are greatly shaped by people. In fact, human actions as well as cultural and societal processes inseparably intertwine and interact with urban ecosystems, forming urban socioecological systems (Grimm et al. 2008; McPhearson et al. 2016; Pickett et al. 2016). The impossibility of separating human parts of urban biodiversity is especially apparent when biodiversity is considered at a more abstract level than species composition, for example, when considering the functional dimension of urban biodiversity (Noss 1990).

Urban biodiversity and green areas provide well-being to urban people in many ways (Tzoulas et al. 2007), such as urban green providing ecosystem services that can improve urban living conditions and health. The concept of multifunctional urban green infrastructure is an attempt to account for all the benefits that different urban green spaces provide to urban people as well as biodiversity in the planning of sustainable cities (Tzoulas et al. 2007; Andersson et al. 2014; Hansen and Pauleit 2014; Lynch 2016; Capotorti et al. 2019). Many ecosystem services derive from ecological processes, enabled by ecological communities and structures (Kremen 2005; Haines-young and Potschin 2010). Thus, one aim in the planning of multifunctional green infrastructure is to identify and preserve diverse and resilient ecological communities of urban flora and fauna. This ensures the consequent ecosystem processes and services (Andersson 2006; Dearborn and Kark 2010; Mace et al. 2012; Ahern 2013; Harrison et al. 2014; Ziter 2016). Social aspects of green infrastructure, such as equitable access to green areas among all resident groups, are also important to consider in order to achieve both ecologically and socially sustainable cities (Wolch et al. 2014; Jerome et al. 2019).

Globally, urbanization is expected to continue for decades (United Nations 2019) and is therefore seen as a conservation issue, as biodiverse seminatural and natural habitats become transformed into urban areas (Marzluff 2002; Ricketts and Imhoff 2003; Seto et al. 2012; Soanes et al. 2018). The high cost of land and interest in new development hinders urban conservation which cannot really stop the pressure for urban growth, only relocate it (Bekessy and Gordon 2007; Dorning et al. 2015; Haaland and van den Bosch 2015).

Urban biodiversity and the provision of ecosystem services can, at least to some extent, be ensured and strengthened, even in dense urban areas with proper planning, design, and management (Lovell and Taylor 2013; Garrard et al. 2018; Artmann et al. 2019; Hansen et al. 2019; Heymans et al. 2019). Ultimately, however, conservation of biodiversity in cities also requires a sufficiently large amount of green areas (Beninde et al. 2015).

When considering biodiversity, both in and outside cities, it often becomes unclear whether preserving inner-city green areas or preventing urban expansion is a better strategy for conservation in general. For some taxa, minimizing the coverage of urban areas is the most beneficial option, but for others, a less dense urban structure with lots of urban green fits better. This dilemma is called ‘the sharing versus sparing’ problem (Sushinsky et al. 2013; Soga et al. 2014) and, in addition to urbanization, it is apparent in all human land-use such as agriculture (Egan and Mortensen 2012). Generally, many academics have concluded that biodiversity conservation should be incorporated with less-intensive land-use, at least in some types of landscapes (Opdam et al. 2006; Cai and Pettenella 2013; Kremen and Merenlender 2018; Reider et al. 2018).

1.2. PROTECTING BIODIVERSITY IN THE FINNISH LAND-USE PLANNING SYSTEM

In Finland, regulative planning has generally played an important role (Lapintie 2015). Box 1 summarizes the hierarchical land-use planning system in Finland as specified by legislation. The system consists of normative guidelines and of spatial zoning plans at three scales: regional, municipal, and detailed. Each legally binding land-use plan is a map that shows the primary land-use types (e.g. residential, industry) allowed in different zones accompanied by guidelines and instructions for development and construction (either specific to zones or general for the entire planning area). In practice, the Finnish land-use planning systems has some additional features, for example when planning along rural shores, but in cities, the simplified system presented in this thesis generally applies.

In the Finnish land-use planning discussion, there is currently a strong demand for densifying urban structure, especially regarding planning of major cities (Niitamo and Sjöblom 2018). Densification and 'new urbanization' are seen as a solution to the prevention of urban sprawl, enabling a more sustainable transport system, and meeting the growing demand for urban living environments (e.g. Helsinki City Plan 2016). Furthermore, in recent years, there has been debate over changing the land-use planning system to become more strategic and less detailed in Finland, especially in growing city regions (Ahonen 2017). Some recent land-use plans have been less straightforward and more inaccurate in appointing different land-use zones spatially than their predecessors, for example the recent master plan for the City of Helsinki (Helsinki City Plan 2016).

Despite the currently strong demands for urbanism and less-detailed planning, preserving ecological values, biodiversity, and ecological connectivity is also a major goal in Finnish land-use planning. Finland has ratified many international agreements (e.g. CBD 2010; IPBES 2019c) that require the country to preserve its biodiversity. In addition to nature protection legislation, maintenance of biodiversity is promoted in the land-use planning legislation. For example, all plans must aim at "preserving biodiversity" and be based on "sufficient inventories" of biodiversity values according to the Land-Use and Building Act. In reality, however, only the species, habitats, or areas protected by the law *must* be accounted for in the land-use plans; the rest is up to planners and decision-makers.

Many Finnish municipalities including major cities have their own strategies and inventories considering green areas and biodiversity protection, for example the Nature Protection Program of the City of Helsinki (Erävuori et al. 2015) or the list of Important Nature Areas of the City of Espoo (Lammi & Routasuo 2012). Furthermore, many planning authorities have tried to adopt new planning concepts such as ecosystem services of green infrastructure, often by using different forms of collaborative planning between planners and other professionals or with the public (Faehnle et al. 2014; Kopperoinen et al. 2014; Brunet et al. 2018; Di Marino et al. 2019; Lähde and Di Marino 2019). The maintenance of ecological networks and connectivity is also an often-mentioned requirement of Finnish land-use plans (e.g. the Finnish Biodiversity Action Plan 2012; National Land-Use Guidelines 2017). This usually results in linear corridor-type symbols, especially in regional and master plans. Many cities aim at identifying their ecological networks and connections for land-use planning (e.g. Ojala 2019).

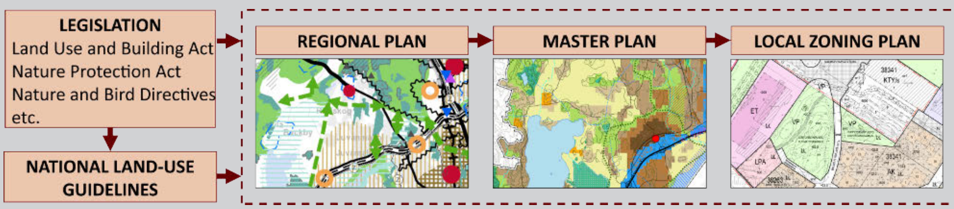
Social welfare and equality between all residents have been a major objective in the Finnish land-use planning and cities actively act against segregation (Bernelius and Vaattovaara 2016). Urban planners

BOX 1. FINNISH LAND-USE PLANNING SYSTEM

The normative framework for land-use planning is most importantly defined by the legislation, the Land-Use and Building Act being the most important one. Regarding biodiversity, the Nature Protection Act, the Forest Act, and EU's Nature and Bird Directives are also important. Legislation is complemented by National Land-Use Guidelines that set general land-use planning norms for each region. In addition to state-level norms, land-use plans can be further steered by e.g. municipal strategies.

Regional plans ("maakuntakaava" in Finnish) are prepared by the Regional Councils of Finland, and they are to balance the needs of e.g. residential and economic development, functioning transport, the energy system, regional-level recreation, preservation of ecological and cultural values, and agriculture and forestry and other types of extraction of natural resources. The scale of the plan is regional. The *municipal master plan* ("yleiskaava") is the comprehensive land-use plan for a municipality. It shows, among other things, the main residential and economic zones, major transport corridors, and major green areas at a comprehensive level. *Detailed zoning plans* ("asemakaava") steer land-use at the local scale (from a single property to a district) and they show the exact borders of properties, roads, parks, and other necessary features. Zoning plans can be very detailed, regulating for example shape and materials of the buildings, colors of the façades, vegetation in a green area, etc.

A noteworthy feature in the Finnish land-use planning system is that all planning belongs to the public authorities. Regional plans are made by the Regional Councils, and municipalities have a complete monopoly over master plans and detailed zoning plans, even on privately owned land.



The pictures' sources (from left): Uusimaa 2050 regional plan proposal (Regional Council of Uusimaa); master plan proposal for Northern Espoo (City of Espoo); detailed zoning plan proposal of Nallenrinne district (City of Helsinki).

have thus acknowledged the social importance of urban green areas, in addition to ecological values (e.g. City of Helsinki 2016). How ecological and social values of green areas will be preserved in the rapidly growing and densifying city regions may become a great challenge, especially if urban growth will be regulated at a more strategic level.

1.3. SPATIAL PRIORITIZATION IN CONSERVATION PLANNING

Conservation science is an attempt to tackle the biodiversity crisis (Soulé 1985).

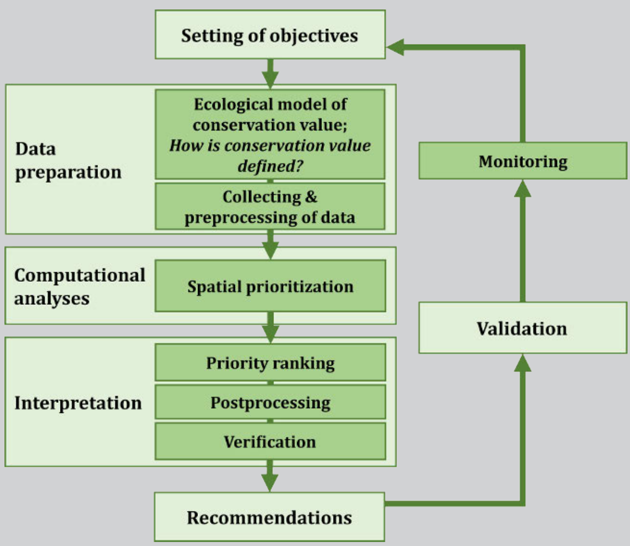
Its topics span many disciplines and include, for example, defining the appropriate measures to describe biodiversity and the formalization of conservation problems (Noss 1990; Humphries et al. 1995; Feest et al. 2010; Simmonds et al. 2019), describing the spatial patterns of biodiversity (MacArthur & Wilson 1967; Martin 2018), describing human influence on biodiversity (Tilman et al. 1994; Seto et al. 2012), combining conservation with economics (Costanza et al. 1997), the building of institutions to monitor and tackle biodiversity loss (Mace and Lande 1991), and embedding conservation into wider decision-making systems (Knight et al. 2006). An important question is *where* nature should be conserved (Myers et al. 2000; Miller and Hobbs 2002).

One of the current paradigms of conservation science is 'systematic conservation planning', which aims to identify appropriate conservation priorities and actions and assist in the effective implementation of those actions in a scientifically sound manner (Margules and Pressey 2000; Knight et al. 2006; Sarkar and Illoldi-Range 2010). An important part of this field is 'spatial (conservation) prioritization' for the identification of optimal locations for different conservation actions (Ferrier and Wintle 2009; Kukkala and Moilanen 2013; McIntosh et al. 2017). Spatial prioritization aims at cost-efficient and effective conservation, meaning that it tries to find solutions that protect biodiversity at large while accounting for limitations (such as costs and land availability) and other potentially relevant factors such as pressures (threats) on species and habitats, ecosystem services, and other land use needs (Kukkala and Moilanen 2013; Kujala et al. 2018a). Importantly, spatial prioritization follows the complementarity principle that can be loosely defined as the aim to identify sets of areas that jointly cover maximal biodiversity (e.g. species, habitats) in a balanced manner, including both rare and common features (Wilson et al. 2009; Kukkala and Moilanen 2013). Spatial prioritization is a rather computationally-driven field of science and there are many software and algorithms available for prioritization; Marxan (Ball and Possingham 2000) and Zonation (Moilanen et al. 2005) being the two most commonly-used ones (Sinclair et al. 2018).

Box 2 summarizes the workflow of a spatial prioritization project. Acquiring the spatial input data about biodiversity is often the most time-consuming phase. Input data usually includes GIS layers about distributions of *biodiversity features*, most often spatial distributions of species, habitats/ecosystems, and ecosystem services (Kullberg and Moilanen 2014). The number of input layers can be up to tens of thousands in prioritization analyses (Pouzols et al. 2014). The importance of acquiring and developing appropriate, adequate, sufficient, and up-to-date input data cannot be overemphasized; with poor-quality on insufficient data, or data that is irrelevant for the planning case, one can only draw limited and assumptive conclusions, even if the technical prioritization analyses themselves would be running perfectly (Lehtomäki and Moilanen 2013; Kujala et al. 2018a). A lack of detailed spatial data often leads to the use of expert opinion

BOX 2. WORKFLOW OF SPATIAL PRIORITIZATION

The schematic figure below presents the workflow of spatial prioritization based on Lehtomäki and Moilanen (2013) and Lehtomäki et al. (2016). The first stage is to define the general objectives for the analysis. Is the aim to locate new candidate sites for reserve network expansion, or is it to find the ecologically least important areas, in which urban expansion would do the least harm for biodiversity? The second stage is referred to in the literature as preparing the 'ecological model of conservation value'. More simply put, this stage includes all the technical decisions and settings that best meet the previously defined aims. Which data should be used? Should the analysis be based only on data about biodiversity, or should the human perspective be included? Is species X relevant? How are different input features weighted? How is connectivity accounted for? The next stage includes collecting the relevant input data and modifying it so that it is technically compatible with prioritization and, once again, is aligned with the general objectives of the analysis. This stage is usually the most time-consuming. Next comes the actual computational prioritization analysis itself. Usually, prioritization is developed in phases in which the complexity of the analysis is increased step-by-step. This stage is followed by interpretation, verification, and possibly post-processing of the prioritization results. Which areas or priority levels are relevant in this case? Which kind of visualization most intuitively delivers that information? Is there a need for quantitative post-processing? Do the maps and curves make sense? Finally, prioritization results allow providing recommendations to e.g. conservation or land-use planners or policy makers. Ideally, prioritization outcomes should be validated, and their success should be monitored through time, and, if needed, prioritizations should be revised based on the new information. In reality, however, these last stages are far too often lacking.



(Martin et al. 2012) or indirect indicators called surrogates (Moilanen 2012), for example, the amount of dead wood that generally indicates high forest biodiversity. Although expert input has its limitations, such as overconfidence and biases, it can be a valuable data source when systematic empirical data is missing (Speirs-Bridge et al. 2010; Martin et al. 2012; Kopperoinen et al. 2014).

Spatial prioritization has been used on many levels of spatial scale including: global (Pouzols et al. 2014), continental (Kukkala et al. 2016), national (Snäll et al. 2016), and local (Gordon et al. 2009), and within different environments including marine (Álvarez-Romero et al. 2018), forests (Lehtomäki et al. 2009), agricultural (Arponen et al. 2013), and urban areas (Gordon et al. 2009; Bekessy et al. 2012). Spatial prioritization has been used both for more academically oriented research and development as well as implementation-oriented planning (Sinclair et al. 2018). Most often, the planning cases fall under the umbrella of conservation (Sinclair et al. 2018) but, in some cases, spatial prioritization has been integrated into a general land-use planning process (Pierce et al. 2005; Botts et al. 2019).

Spatial prioritization is typically embedded into a wider 'conservation planning' context (Margules and Pressey 2000; Knight et al. 2006; Kukkala and Moilanen 2013) which includes all the necessary steps, from setting up the proper conservation objectives to the on-the-ground implementation of different conservation actions. Within the context of conservation planning, the role of spatial prioritization is to utilize data to find optimal locations for the desired actions: protection, management, or restoration actions, etc. (Kukkala and Moilanen 2013). The actual implementation of those actions must address the question of *how* conservation should be executed, including all the relevant social, political, and economic requirements for achieving conservation goals, such as negotiations with landowners and forming ecologically beneficial policies. (Knight et al. 2006, 2011; McIntosh et al. 2017). Efficient and informative spatial prioritization would account for different limitations for conservation, such as land-use economics, in advance (Di Minin et al. 2013).

1.3.1. CONNECTIVITY IN CONSERVATION PLANNING

Connectivity is one of the three fundaments, alongside habitat amount and quality, determining a landscape's capability to support species populations (Hodgson et al. 2009, 2011). The importance of connectivity for effective conservation is generally acknowledged, yet, the appropriate means to account for it have already been debated for decades (Taylor et al. 1993; Puth and Wilson 2001; Boitani et al. 2007; Gippoliti and Battisti 2017; Miller-Rushing et al. 2019). There is a myriad of methods to define and model connectivity and identify parts of landscapes that contribute to connectivity (Chetkiewicz et al. 2006; Kindlmann and Burel 2008; Rayfield et al. 2011; Correa Ayram et al. 2016).

Connectivity is often separated into two types: structural and functional connectivity. Structural connectivity refers to how contiguous habitat patches or other homogeneous landscape types are (Taylor et al. 1993), whereas functional connectivity accounts for the dispersal capability of the target taxon in different landscape types (Bélisle 2005). Another operationally important division is whether connectivity is considered from the perspective of an individual site ("are there other habitat patches nearby etc. that support the population(s) in the focal site?") or from the perspective of wider ecological networks ("what is the role of the focal site to other habitat patches in the landscape?").

In connectivity conservation that builds upon the metapopulation theory (Hanski 1998), landscapes are usually divided into core areas, such as reserves or main breeding habitats of target species, plus the rest of the landscape – the so-called matrix. A very common application of connectivity in conservation are the ecological corridors, that is, contiguous elements that facilitate species' dispersal between core areas through the matrix and that should be preserved and/or enhanced to support the persistence of populations (Puth and Wilson 2001; Chetkiewicz et al. 2006). Many studies, however, have questioned the benefits of narrow corridors through human-modified landscapes (Mutanen and Mönkkönen 2003; Gilbert-Norton et al. 2010; Pérez-Hernández et al. 2014). In reality, the matrix is not uniformly unsuitable for species but can also support species reproduction and dispersal to varying degrees (Fischer and Lindenmayer 2006; Reider et al. 2018). Furthermore, recent analyses propose that, in fragmented landscapes, the small and isolated patches of higher habitat quality also contribute greatly to landscape-level biodiversity (Wintle et al. 2018; Volenec and Dobson 2020). Connectivity should therefore not be the only focus in conservation over habitat amount and quality (Hodgson et al. 2011).

1.3.2. THE ZONATION SOFTWARE FOR SPATIAL PRIORITIZATION

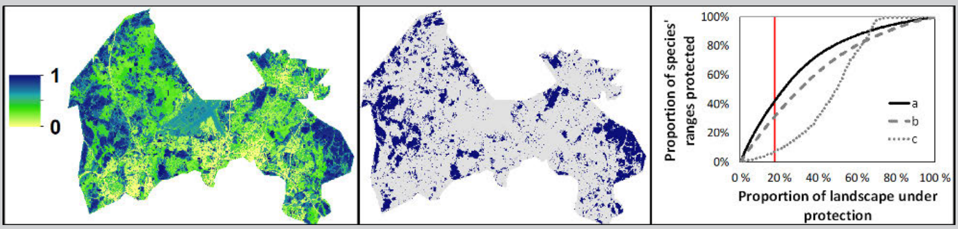
Zonation (Moilanen et al. 2005, 2011a; Lehtomäki and Moilanen 2013) is one of the currently available software implementations of spatial prioritization, and the one I have used in my thesis. Zonation has been developed in the early 2000s at the University of Helsinki. Since then, it has become widely used in conservation planning throughout the world (Sinclair et al. 2018).

1.3.2.1. General working principles of Zonation

Zonation's basic working principle could be described as iterative ranking of landscape sub-units while minimizing the marginal loss for biodiversity and accounting for complementarity and balance between all input features (Moilanen et al. 2005). Input features are raster-type GIS layers, which usually describe distributions of biodiversity, (e.g. species, habitats, or ecosystem services) but can include other types of features as well (e.g. **II**). First, Zonation assumes that the best case for all input features is that the entire study area is protected. Then, it identifies those sub-areas, usually raster cells, that constitute the lowest marginal value for all input features. Then, it removes those areas, assigns them with a priority value, and updates the remaining distributions for all input features. Zonation repeats these steps, identifying and re-

BOX 3. MAIN OUTPUTS OF ZONATION

The simplified figure below demonstrates Zonation's two main outputs, the 'priority rank map' and the so-called 'performance curves', which should always be interpreted jointly. The left panel depicts a simple priority rank map from the City of Vantaa. The rank map is a raster-type GIS layer and its cell values are always linearly scaled from 0 to 1, 1 being the highest priority. Priorities are nested, i.e. the top-5% are within the top-10% and top-2% are within top-5%, etc. From the map, one can assess and compare the conservation priorities of different sites. If, for example, 20% of the landscape were desired for conservation, then the top-20% priority areas (middle panel) would be the most optimal ones (according to this analysis). The performance curves on the right show the proportion of remaining occurrences in different priority levels separately for 3 input features (here, species). Curves can be used to assess the sufficiency of different priority levels for each input feature. One typical way to interpret the figures below would be: "It has been politically decided that 20% of Vantaa's green areas will be protected. According to the prioritization (left panel), it is the sites in the middle panel that should be protected. This corresponds to preserving roughly 40, 35, and 5% of the current distributions of the species a, b, and c, respectively (right panel)".



Zonation produces also other types of output files such as the *weighted range-size corrected richness* map ('wrscr') that summarizes weighted range size rarity of input features. Those, however, I will not discuss in detail in this thesis.

moving areas which constitute the smallest marginal loss in the distribution of its input features, resulting in a complete prioritization of the entire study area. The marginal loss in each iteration is determined by the original and remaining distributions of each input feature, as well as other additional factors, such as weights, connectivity, costs, and the balancing method, often called the cell removal rule (see below).

The working principle of Zonation makes it different from other often-used prioritization software, such as Marxan, that require pre-defined targets for conservation (e.g. that all features must have 17% of their original distributions covered) (Delavenne et al. 2012; Lehtomäki and Moilanen 2013). Instead, Zonation allows assessing how different fractions of the focal landscape relate to the representation of input features. Therefore, Zonation is well-suited to complex land-use planning cases that combine many types of social and ecological features, as defining suitable targets for each feature can be a difficult and political question of its own.

Zonation's two main outputs, the priority rank map and the so-called performance curves, are explained in Box 3.

1.3.2.2. Major Zonation settings and features

One of, if not *the* major setting in Zonation is the cell removal rule, or, in other words, the rule by which Zonation calculates the marginal loss for biodiversity and implements balancing during its iterations. The two most common options are the Core Area Zonation (CAZ) and Additive Benefit Function (ABF). With CAZ, the marginal loss is determined by the rarest input feature and with ABF, the loss derives from the weighted range size rarity sum of all features. In other words, CAZ emphasizes the rarity of input features and aims to ensure that high-quality locations remain for every feature in the study area (within all priority levels for as long as possible), whereas the ABF option emphasizes more the richness over all input features (Moilanen 2007; Lehtomäki and Moilanen 2013). Another important consideration in Zonation is how different input features are weighted. Each feature can be weighted individually based on their red-list status, endemicity, or economic value, for example (Lehtomäki and Moilanen 2013). The weighting system should be aligned with the case-specific objectives of each prioritization analysis (Box 2). Furthermore, Zonation includes a variety of features to account for many relevant things in conservation planning, such as costs (Cabeza and Moilanen 2006), interactions between species (Rayfield et al. 2009), current land-use (Moilanen et al. 2011b), existing protected areas (Mikkonen and Moilanen 2013), and many more.

Zonation's post-processing tool, LSM Landscape Identification analysis (Moilanen et al. 2005), can support impact assessments. The analysis shows the proportions of all input features' distributions inside any pre-defined area. In other words, the analysis answers the question "how large of a share of species X's, Y's and Z's known distributions are located within this area?"

1.3.2.3. Connectivity in Zonation

There are many ways to account for connectivity in Zonation analyses (Lehtomäki and Moilanen 2013). Some of them aim for spatial compactness or structural connectivity of prioritization results, such as Boundary Length Penalty (Moilanen and Wintle 2007) or the corridor building method (Pouzols and Moilanen 2014). Some of them stem from the metapopulation theory and can account for (estimated) dispersal capabilities of individual input features (i.e. the functional connectivity), such as Distribution Smoothing (Moilanen et al. 2005) or Neighbourhood Quality Penalty (Moilanen et al. 2008). Matrix connectivity (Lehtomäki et al. 2009) is often used in Zonation analysis. It accounts for the assumption that some input features can support other ones to varying degrees, if they are located inside a spatial scale at which the focal feature can utilize the local landscape, scaled by a feature-specific dispersal kernel. For example, different forest types (inside a reasonable spatial range) could be considered to support each other; for many forest species, it is almost as good to have pine forests next to spruce forests than to have a larger spruce forest patch. Then again, species in those same spruce forests might be less, but still somewhat, supported by nearby birch forests.

Corridor-Zonation refers to the corridor-identification method in Zonation (Pouzols and Moilanen 2014). In the method, a penalty is given for fragmenting high-priority areas. As a result, top-priority patches will tend to remain united by linear elements such as corridors. The minimum width and the strength of the penalty must be pre-defined. However, Zonation does not require any preset information about core areas or starting points of corridors as it balances between local habitat quality and corridor connectivity throughout the prioritization.

2. STUDY AREAS

2.1. THE UUSIMAA REGION

The Uusimaa region (henceforth, Uusimaa) on the southern coast of Finland is the most populated of the 18 regions in Finland and includes the Finnish capital district. Uusimaa covers 9,600 km^2 and 1.7 million people live there. The region is further divided into 26 municipalities (as of 2020).

Nature in Uusimaa is generally under heavy human influence, at least in Finnish terms. Uusimaa's green structure mainly consists of intensively-managed agricultural areas and forests, most of which are commercially managed (Fig. 1). There are, however, many areas in ecologically good condition as well, including, for example, old-growth forests, mires, eskers, lakes and rivers, and rural biotopes (Kuusterä et al., 2015). Coastal and archipelagic areas are also characteristic to Uusimaa. There are three natural parks and many Natura 2000 and other types of protected areas in the region.

Compared to other Finnish regions, very heavy population growth is expected in Uusimaa; the population is estimated to grow by 500,000 by 2050, mainly in the capital district (Regional Council of Uusimaa 2019). At a regional level, this growth is steered by the regional zoning plan, prepared by the Uusimaa Regional Council as the responsible authority. The works in my thesis relate to two regional plans in the Uusimaa region. The first one is the so-called '4th-phase regional plan' (Regional Council of Uusimaa 2017). Since 2006, the Regional Council of Uusimaa has prepared new regional plans in thematic phases instead of a comprehensive plan. The 4th-phase plan focused, among other things, on regional biodiversity, recreation, and ecological networks, and came into effect in 2017. To support this plan, a comprehensive Zonation analysis was done to identify ecologically important areas to be ensured in the regional plan. The original report is in Finnish by Kuusterä et al. (2015). The major part of the project was to collect existing bio- and geodiversity data in the region.

In 2017, the Regional Council started developing the next comprehensive regional plan, the so-called 'Uusimaa 2050 regional plan' (Regional Council of Uusimaa 2019). Compared to previous regional plans, this plan is intended to be more strategic and allow more freedom in the municipal-level land-use planning. It is intended to be in effect until the year 2050. As a part of this plan, the information about regional ecological networks and connections was updated using Zonation. The original Finnish report is by Jalkanen et al. (2018a). Zonation was also used in the impact assessment of the Uusimaa 2050 plan proposal (Jalkanen et al., 2018b).

2.2. THE HELSINKI METROPOLITAN AREA

The Helsinki Metropolitan area (770 km^2) consists of four municipal cities, Helsinki (the capital of Finland, population 650,000), Espoo (290,000), Vantaa (230,000), and Kauniainen (10,000). Although the cities plan their land-use individually, they form a uniform urban agglomeration as well as an ecological entity.

Figure 1 Land-cover in the Uusimaa region (CORINE 2018), which is mostly dominated by forests (mostly in forestry use) and agricultural areas. The Helsinki Metropolitan area is the major urban agglomeration in the region but other smaller cities exist in the region as well. The landscape in Uusimaa is most of all a mixture of agricultural areas and forests (upper photo, Porvoo, E-Uusimaa). Coastal areas (bottom-right photo, Inkoo, W-Uusimaa) and freshwater environments (Mäntsälä, N-Uusimaa), among others, are also characteristic to the region.

Figure 2 shows the green area structure in Helsinki Metropolitan area. As a typical Scandinavian city region, there are great amount of semi-natural and natural green areas in Helsinki Metropolitan area (Kabisch et al. 2016). The area has a large urban fringe which consists mainly of forests and includes two national parks. There are also large and contiguous semi-natural green areas (the 'green fingers') that expand close to the urban center. Apart from forests, there are many types of urban green spaces in the area including constructed public parks, allotment gardens, old military fortifications, agricultural fields, brownfields, rocks, urban meadows, coastal and freshwater environments, and wetlands (Vierikko et al., 2014). There are several Natura 2000 areas and smaller protected areas in the metropolitan area.

The Helsinki Metropolitan area is growing rapidly; its growth forms almost 90% of the expected growth of the entire Uusimaa region (Regional Council of Uusimaa 2019). Historically, urban sprawl has been relatively strong in the metropolitan area and its surroundings. When Helsinki has grown slowly, its surrounding rural and suburban municipalities have grown more rapidly, and vice versa (Laakso, 2012). In the local urban planning discussion in the Helsinki Metropolitan area, there is currently a strong demand for densifying urban structure to prevent sprawl and to gain diverse urban amenities (Niitamo and Sjöblom 2018). This has resulted in many developments along, for example, new rail connections such as expanded metro and commuter train lines and new light rails. However, there exists also a strong will to preserve ecological values, connectivity, and the ecosystem services that urban green areas produce (e.g. City of Helsinki 2016).

Figure 2 The green structure of the Helsinki Metropolitan area (CORINE 2018). Large green areas, most of which are different types of urban and seminatural forests (top-left photo, Keskuspuisto, Helsinki), expand near the urban center. There are also many other types of green areas in the region such as managed parks (top-right, Kaivopuisto, Helsinki), allotment gardens (bottom-left, Viherkumpu, Vantaa) and anthropogenic wetlands (bottom-right, Finnoo, Espoo).

3. MATERIALS AND METHODS

3.1. THESIS OUTLINE

My thesis consists of the synopsis and four articles, all of which include spatial prioritization. Figure 3 compares the studies in the light of the general workflow of spatial prioritization (Box 2).

I contributes to the thesis by providing understanding of how urban biodiversity should be measured and treated in spatial prioritization of urban green areas. This is so that the analysis would be meaningful for the urban ecosystem and green infrastructure perspective compared to mere representation of rare species, for example. The paper demonstrates a method of urban prioritization which builds upon the framework of Biodiversity Quality (Feest 2006; Feest et al. 2010). In **II**, the same areas are assessed but entirely from the human perspective by introducing a novel method for spatial prioritization of green areas, using their travel-time-based human accessibility and hence, utility for recreation. The paper shows that the complementarity principle of spatial prioritization can result in, not only high gains in biodiversity protection, but also improved social equality in green area provision.

III and **IV** add a regional planning perspective to the thesis. Both papers are based on projects under the Regional Council of Uusimaa, in which a series of Zonation analyses were done to inform regional planning. The papers are based on reports (in Finnish) about the top-priority biodiversity areas in Uusimaa (Kuusterä et al., 2015), ecological networks and connections in the region (Jalkanen et al., 2018a), and the impact assessment of the Uusimaa 2050 regional plan proposal (Jalkanen et al., 2018b). **III** describes how Zonation analyses were used as a part of the general regional zoning process and which types of institutional and data requirements the operational land-use planning context brings to the prioritization process. This discussion is continued in **IV** which introduces a method for identifying large ecological networks with spatial prioritization. In the paper, we also used the less-utilized Zonation method for identifying ecological corridors. Both **III** and **IV** include parts of the impact assessment of the Uusimaa 2050 plan, **III** from the "general" perspective of the priority areas, and **IV** in the regional connectivity perspective.

3.2. DATA

As spatial prioritization is, by definition, a type of spatial analysis, spatial data is a requirement for the analyses. The input of spatial data was about biodiversity in **I**, **III**, and **IV** and human accessibility in **II**. Spatial data about current protected areas and land-use was also used in **III** and **IV**. Input from local taxonomic and nature experts was crucial for **I**, **III**, and **IV**, as is very often the case in conservation planning and spatial prioritization (Martin et al. 2012; Lehtomäki and Moilanen 2013). Detailed descriptions of the data can be found in the original articles.

3.2.1. SPATIAL DATA ABOUT BIODIVERSITY

The focus, and, consequently, data used in **I**, **III**, and **IV** was about biodiversity.

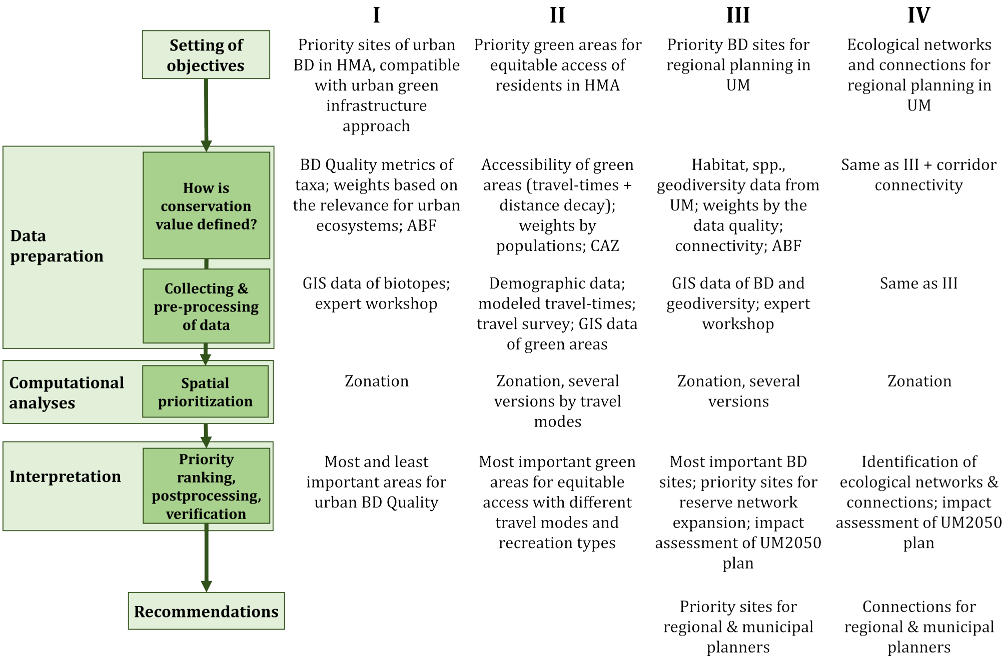


Figure 3 Steps of each study, following the workflow in Box 2. All studies include using the Zonation software for spatial prioritization but for different purposes and in different contexts, and with different data and settings. BD = biodiversity, HMA = Helsinki Metropolitan area, UM = Uusimaa region, UM2050 plan = Uusimaa 2050 regional plan proposal (Section 2.1), ABF = Additive Benefit Function (Zonation-specific setting), CAZ = Core Area Zonation (Zonation-specific setting).

In **I**, I first compiled a map about urban land cover (urban biotope map) from the Helsinki Metropolitan area that was later scored into a habitat suitability maps by taxonomic experts (see Section 3.2.3). In the study, we used the biotope concept of classifying urban habitat/land cover types based on their characteristics in, for example, vegetation type, soil properties, and management history (Sukopp and Weiler 1988; Löfvenhaft et al. 2002). The urban biotope map showed the distributions of 54 different biotopes which ranged from different anthropogenic (e.g. constructed parks, golf courses) to semi-anthropogenic (e.g. open brownfields) to natural urban biotopes (e.g. old-growth forests, mires). The biotope map was mosaicked from 27 different spatial data sources such as local municipal cities, local regional council (of Uusimaa), and national Finnish institutions (e.g. Finnish Environment Institute).

The aim of **III** and **IV** was to synthetize all relevant biodiversity data into a form (i.e. priority ranking) that supported local regional planning. It was therefore important that the analyses included all habitat and species data that are also otherwise used in the Finnish land-use planning and environmental administration, and that describe the biodiversity in the region as comprehensively as possible. A biodiversity data layer was included in the prioritization analyses if all of the following requirements were met: (i) it included ecologically relevant information (e.g. distribution of a species or quality of a habitat), (ii) it covered the entire study area (the Uusimaa region and a 15 km buffer), (iii) it was of good quality and up-to-date, (iv) we were able to access metadata on the production chain of the data, (v) its resolution/scale was detailed enough for the analysis, and (vi) together with other data, it constituted of a diverse group of biodiversity features that could answer to the wide planning needs. Finally, input data included 59 layers about habitats, species, and geodiversity.

Preprocessing of the biodiversity data so that it was meaningful for the prioritization analyses was a major part of the work in **III**. Data was rather heterogeneous which meant that data layers needed to be processed in several ways. Data layers were, for example, treated differently if they were originally precence/absence type data (e.g. otter *Lutra lutra* observations), discretely classified (e.g. ruderal biotopes that were pre-classified based on their conservation importance), or continuous (e.g. layers describing forest volume and age). Some species datasets, such as observations of endangered species (TAXON database) had to be combined into a "summary layer" that showed the observations of all endangered species as the scarcity of observations prevented making reliable maps for individual species.

3.2.2. OTHER TYPES OF SPATIAL DATA

In **III**, some analyses included the existing protected areas in Uusimaa (Section 3.3.1). All national, private, and Natura 2000 reserves were included into a binary layer. **III** and **IV** also included the estimated habitat degradation caused by past and present human pressures as a so-called 'condition layer' (Section 3.3.1). Current land-use was mapped mainly from the CORINE Land Cover 2006 dataset (EEA 2020) and complemented with more detailed information, such as second-home areas from different authorities. For the impact assessment of the Uusimaa 2050 plan proposal (**III**, **IV**), a GIS version of the zones was received from the Regional Council of Uusimaa and pre-processed to be appropriate for the Zonation analyses.

3.2.3. EXPERT OPINION

In **I**, 24 local taxonomic experts, representing ten taxa, scored each urban biotope based on how well each of them supported different Biodiversity Quality attributes (richness, biomass, abundance, evenness, uniqueness, habitat specialists, and regional representativeness) of their taxon. In this phase, all experts worked individually. Later, experts participated in an expert workshop, in which they determined weights for each input layer (i.e. Biodiversity Quality attributes and taxonomic groups) as well as the spatial scale for the use of landscape for each taxa for spatial aggregation in Zonation (Section 3.3.1). Experts defined taxon-specific weights (for Biodiversity Quality attributes) and spatial scales of landscape use in small groups, and weights for all taxa together. Instead of using mean values of expert answers, all parameters were discussed until a consensus between all experts was reached (Martin et al. 2012).

In **III** (and consequently **IV**), 21 environmental experts from local stakeholder groups (major municipalities, the Finnish Environment Institute, and nature conservation NGOs) participated in: (i) planning of the pre-processing of different data layers, (ii) defining weights, and (iii) different connectivity parameters. After the first Zonation analyses, the experts (iv) provided feedback on visualizations of the results and (v) evaluated the results. The expert panel met several times, and, importantly, during the first meetings, were familiarized with the basic principles of spatial prioritization and Zonation.

3.2.4. ACCESSIBILITY AND POPULATION DATA

In **II**, we used two major data sets about the accessibility of areas and mobility of people in Helsinki Metropolitan area. Firstly, we used the recent travel survey by the local transport authority (Brandt et al. 2019) to estimate how long people generally take to get into a recreational area with different travel modes (the so-called distance-decay functions). Second, we used the Travel Time Matrix dataset (Tenkanen and Toivonen 2020) that shows the travel-times from each 250-meter population grid cell in the Metropolitan area to every other one, separately for different travel modes. Finnish-state authorities also provided demographic data for the same 250-meter cells, of which we used the total population of residents.

3.3. SPATIAL ANALYSES USING THE ZONATION SOFTWARE

Detailed descriptions of the methods can be found in the original articles.

3.3.1. ZONATION ANALYSES

All spatial prioritization analyses in this thesis were done with Zonation v4.0 (Moilanen et al. 2014). While the major determinant of the Zonation priority patterns is the input data used, many additional settings may, and often do, influence the results as well (Kujala et al. 2018a) (see the original articles for detailed descriptions of the analyses).

One of the main decisions in Zonation is which balancing method (cell removal rule) is used, in other words, how the marginal loss is defined in the prioritization iterations (Section 1.3.2.2). In **I**, **III**, and **IV**, we used the ABF option to emphasize the richness of input features in the prioritization and their nature as surrogates for broader biodiversity. **I** aimed to identify diverse urban ecosystems and **III** and **IV** aimed to locate areas of importance for biodiversity to be secured in regional planning. Input data in all studies was considered to act as a surrogate for biodiversity more generally, making the ABF option appropriate (Lehtomäki and Moilanen 2013). Even in the ABF analyses, the relative rarities of the input features have a great effect on the priority patterns. In **II** on the other hand, CAZ was more appropriate because it emphasized those city districts that had the least green areas available, resulting in increased emphasis on the social equality in green area provision between different districts — the focus of the study.

Another important decision in Zonation is how each input feature is weighted (Lehtomäki and Moilanen 2013) which should correspond to the general aims of the prioritization. In **I**, weighting was done in an expert workshop and was based on the relevance of each included taxa for the functioning, resilience, and sustainability of the local urban ecosystem in the Helsinki Metropolitan area (Section 3.2.3). In **III** and **IV**, the weights of each input feature were also defined by an expert panel in a consensus-based manner. Weights of input features were based on data quality and their relevance for conservation. In **II**, we used the number of residents in each district directly as a weight.

We included connectivity in the prioritizations in **I**, **III**, and **IV**. All of them included the so-called matrix connectivity setting in Zonation for spatial aggregation of priority areas (Lehtomäki et al. 2009). The relevant spatial scales for aggregation of each input layer in every study was defined by the engaged experts (Section 3.2.3). Furthermore, **III** and **IV** included connectivity transformations during preprocessing of certain data layers (such as the one showing Cervidae distributions). In **IV**, we also used the so-called Corridor-Zonation (Pouzols and Moilanen 2014) in locating ecological connections in Uusimaa.

III and **IV** also utilized the so called condition layer (Moilanen et al. 2011b) and hierarchical masks (Mikkonen and Moilanen 2013). The condition layer was used to include the estimated general effects of current land-use to regional biodiversity; more intense land-use or environmental noise lowers the ecological quality of habitats at the location. In **III**, current protected areas in Uusimaa were included as a hierarchical mask in some of the analyses. As a result, current reserves received the highest priorities, which allowed us to identify the "next-best" areas that best complement the existing protected area network. In **IV**, we included the large top-priority areas as a hierarchical mask to the Corridor-Zonation analyses to "guide" Zonation to locate connections specifically between the most valuable remaining biodiversity areas.

3.3.2. POST-PROCESSING AND INTERPRETATION OF ZONATION RESULTS

Representing and visualizing results in an informative manner is an important phase in spatial prioritization (Pierce et al. 2005; Lehtomäki and Moilanen 2013). Especially in **III**, visualization of the Zonation results was payed special attention to. The coloring of the priority rank map was designed to visualize the locally relevant priority levels clearly, and the same color palette was included in the figures representing respective performance curves. Importantly, all studies **I**–**IV** report both rank map and performance curves and include a brief description about how to interpret the rank map and curves together in each specific cases. In **I**, ecologically, the least important areas (based on performance curves) were shown in a separate map, demonstrating the use of spatial prioritization for the impact avoidance principle. In **III**, top-priority areas were classified as 'ecologically important areas' ('LUO-alue' in Finnish), delineated separately into a GIS dataset, named uniquely, and described individually (see below) to support further land-use planning.

In **IV**, we combined Zonation's two spatial outputs, the priority rank map and the weighted size-corrected richness map, in a novel way. This allowed us to identify areas in Uusimaa that were at least somewhat important for local biodiversity in general (i.e. areas that were generally rich of biodiversity features and/or harbored some rare features). These areas were separated from more degraded parts of the landscape and, if large and contiguous, were interpreted to form large ecological networks. Furthermore, in **IV**, the identification of ecological connections was not done directly from the Corridor-Zonation results, but by visually comparing the priority maps with and without corridor-building method.

We used the Landscape identification method (Moilanen et al. 2005; Moilanen et al. 2014) for post-processing the Zonation results in **III** and **IV**. The method reports the proportions of distributions of each input biodiversity feature layer in any pre-defined area. In **III**, landscape identification was used to characterize the biodiversity found in each of the ecologically important (LUO) areas, and in **IV**, biodiversity found in large ecological networks. Landscape identification was also used in the impact assessment of the Uusimaa 2050 regional plan proposal (**III**). The method allowed us to quantify the biodiversity that was possibly threatened by different planning zones (e.g. residential areas or highways) or covered by protected areas. In **III**, we developed a new 'feature density index' which describes the "density" of input features in a given site compared to the average of the entire study area. The index allows comparing biodiversity concentrations (i.e. the shares of input features) between areas of different sizes.

4. RESULTS AND DISCUSSION

In this chapter, I summarize the most relevant findings of this thesis and discuss how they relate to the main objectives presented in Section 1. In **I**, I show that many natural and anthropogenic urban biotopes are important for urban Biodiversity Quality (Feest et al. 2010), which should be respected by the local urban and green infrastructure planners. In **II**, I demonstrate that both central green areas as well as small areas at the urban fringe are needed for ensuring equitable access to green areas for all metropolitan residents. In **III**, I show how spatial prioritization was used to identify key biodiversity areas in the Uusimaa region and describe how Zonation analyses were used to support regional planning. Finally, in **IV**, I identified seven large, well-connected ecological networks in Uusimaa as well as many ecological corridors between more fragmented zones that should be ensured in regional planning.

The results of Zonation studies like mine can be poorly summarized into a short section with informative charts and numbers. The interpretation of Zonation rank maps and performance curves can only be done in the light of the objectives and workflows of the analyses (Lehtomäki and Moilanen 2013). Therefore, I advise the reader to see the original articles for the case-specific results, such as the priority rank maps as well as their interpretation. Here, I discuss my conclusions on a more general level.

In general, spatial prioritization can support land-use planning because prioritization produces systematic, balanced, and cost-efficient results with generally high expected conservation gains. However, as I discuss below, there are some important aspects that need to be considered when prioritizations are done in urban areas or with the intention to support general land-use planning.

I have done my work in close collaboration with local and regional planning and environmental authorities, and one of my goals with this thesis has been to produce methods useful and results of value for real-life planning. Therefore, in addition to the academic discussion, I also elaborate on my broad observations and conclusions about spatial prioritization and general land-use planning, especially in Finland.

4.1. SPATIAL PRIORITIZATION FOR OPERATIONAL LAND-USE PLANNING: PRACTICAL IMPLICATIONS

Of the works in my thesis, **III** and **IV** were originally done to support regional zoning (Kuusterä et al. 2015; Jalkanen et al. 2018a) whereas **I** and **II** are examples of more scientific-oriented analyses. My thesis thus reflects the wider use of spatial prioritization, which varies from purely academic research to on-the-ground implementation-focused assessments (Sinclair et al. 2018). The differences between these two contexts, as well as requirements to facilitate implementation of research outputs, have been discussed in conservation biology (Theobald et al. 2000; Knight et al. 2011; McIntosh et al. 2017; Sinclair et al. 2018; Adams et al. 2019). Implementation-oriented studies should focus on the relevance and legitimacy of the outputs, not just their methodological credibility (Cash et al. 2003), and study outputs must be presented in a manner that implementers can understand (Theobald et al. 2000; Pierce et al. 2005; Knight et al. 2011; McIntosh et al. 2017). In their handbook of Zonation projects, Lehtomäki et al. (2016) describe nicely how Zonation projects differ between three different domains: research, issue-driven science, and operational planning, in terms of projects' objectives, end products, decision-making contexts, etc. Below, I discuss some of my practical observations about spatial prioritization in the light of operational land-use planning, mainly based on the experiences from **III** and **IV**.

The need for information which is both legitimate and relevant for regional planning of Uusimaa was reflected by the need for as comprehensive input data as possible (**III**). As one regional planner once put it, for them it was very important to say to local decision-makers, interest groups, and environmental NGOs that all available data layers were included in the analysis, because excluding some layers could have been a reason to contest the legitimacy of the entire analysis. This led to the inclusion of rather heterogeneous data, from point-type observation maps of single species to rasters with continuous values about modeled forest age (**III**, Section 3.2.1). This in turn placed extra demand on careful design of the Zonation analyses, including pre-processing and weighting of different data.

As land-use planning involves coordination and balancing between different objectives and spatial interests (Theobald et al. 2000), it must be able to examine the same areas from different perspectives. In spatial prioritization, this can be provided, to an extent, by doing single prioritizations in versions with alternative input data and settings. In **III**, for example, a series of prioritizations was produced (e.g. with and without freshwater areas, connectivity, current land-use, existing protected areas, etc.) which enabled assessment of the importance of some areas, for example, based on their local habitat quality vs. their role for regional ecological connectivity. No single analysis was claimed as the "final one". Doing analyses in versions has been a part of the Zonation 'culture' since its emergence (Lehtomäki et al. 2016). If Zonation becomes a more mainstream tool in different organizations, I emphasize that, especially in the context of land-use planning, this culture should be maintained.

Apart from emphasizing different perspectives, versioning of analyses is important for verification (Lehtomäki et al. 2016) and for assessing the sensitivity of analysis for variable data and different settings (Kujala et al. 2018a). Zonation results, such as the priority patterns, are more sensitive to some factors compared to others (Kujala et al. 2018a, b). For example, in my experience, small changes in the feature weights hardly affect the priorities. On the other hand, a seemingly small change in the shape of the distance-decay function in **II** had a drastic impact on the entire prioritization because it affected all input data layers. Hence, Zonation experts should be aware of what the analysis is sensitive to, and not spend too much time on fine-tuning data or settings that would have little impact on the final outcome.

When spatial prioritization outputs, such as the rank maps, are to influence implementation, they must be understandable by the people who utilize them (Pierce et al. 2005; Knight et al. 2011; McIntosh et al. 2017). In **III**, visualization of the Zonation results was designed together with the expert panel, which was thought to facilitate interpretation by the stakeholder experts (Pierce et al. 2005; Section 3.3.2). Zonation's priority rank map and the performance curves were always shown together with a check box showing explicitly which analysis version was displayed (Fig. 4). Another important output of the Uusimaa analyses in **III** was the site description cards of each top-priority site, identified with Zonation (the so-called LUO areas; Faunatica and Regional Council of Uusimaa 2016). Effort was put into describing and characterizing each of the 241 top-priority sites to facilitate their conservation, management, and/or accounting for them in the municipal land-use planning. Without efforts like these, utilization of the prioritization outcomes in the many local instances would likely be modest. In operational planning, the Zonation outcomes can be distributed also in GIS format, as was done in the Uusimaa cases. It is then particularly important to carefully and thoroughly explain the characteristics, quality, and applicability of each data product in their metadata, so that future users (e.g. consultants) have a better understanding of what can and cannot be done with the data.

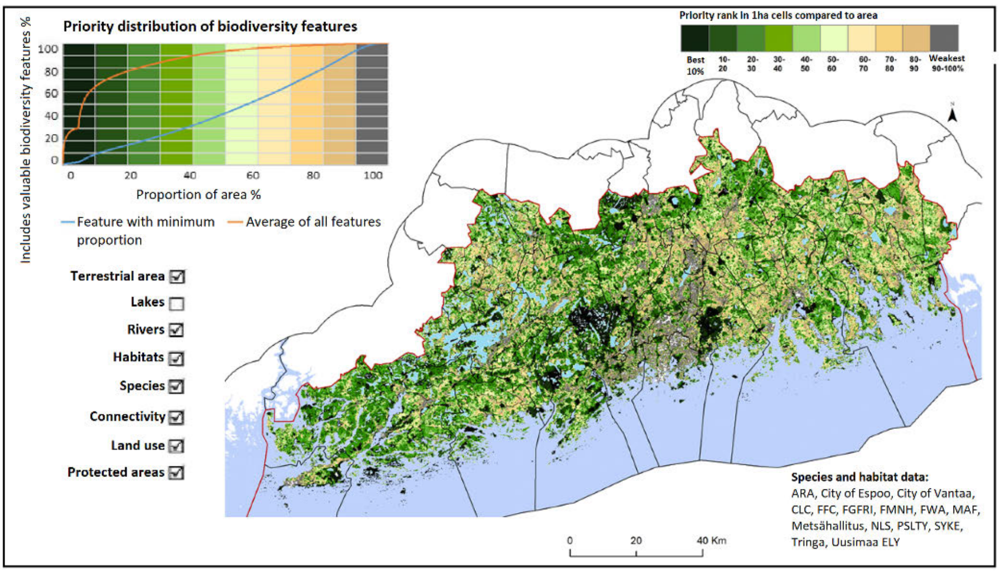


Figure 4 A picture showing results of one Zonation analysis in Uusimaa. The figure includes the priority rank map (with a color palette designed to be case-specifically intuitive), performance curves (with the rank map's color palette as background), data providers, and, importantly, check box showing which features were included in this particular version of the analysis. From **III** and adapted from Kuusterä et al. 2015.

We used the Landscape identification tool (Moilanen et al. 2005; Moilanen et al. 2014; Sections 1.3.2.2, 3.3.2) in both **III** and **IV**. Although the tool is mentioned less in academic literature, it turned out to be very useful in the implementation-aimed analyses. The method allowed us to identify which biodiversity features were characteristic to individual LUO areas (**III**) or large regional networks (**IV**), or to quantify biodiversity that was directly threatened by different land-use zones in the Uusimaa 2050 regional plan proposal (**III**). The feature density index (**III**; Section 3.3.2) allowed us to intuitively demonstrate the importance of LUO areas (that harbored up to 66 times "more" biodiversity than similar-size areas in Uusimaa on average) or to compare the amount of biodiversity concentrated in large networks between each other and, importantly, to areas outside the networks. Although a simple summarizing metric, the feature density index can offer a powerful message about biodiversity concentration in different sites.

Conclusions: It is important that each spatial prioritization serves its purpose as well as possible, as different needs arise in different planning and research contexts. Considering implementation-aimed land-use planning, the need for locally relevant and legitimate information places pressure on data scope and quality, the design of spatial prioritization analyses, and on the interpretation of analysis outputs. In the context of land-use planning, it is important that alternative analysis versions are provided for the end-users. Responsible Zonation experts are aware of and communicate clearly about the needs, workflow, and limitations of Zonation analyses.

4.2. WELL-INFORMED PLANNING REQUIRES SYSTEMATICALLY COLLECTED AND HIGH-QUALITY BIODIVERSITY DATA

This work would not have been possible without the availability of abundant biodiversity data; the variety of biotope data that I could extract in **I**, and the many data layers for habitats, species, and geodiversity in **III–IV**. In many other parts of Finland, similar work would not have been possible due to the lack of data. Spatial prioritization is a data-hungry method and the quality and applicability of the analyses are directly related to the quality of input data (Lehtomäki and Moilanen 2013). Although there are strategies to do prioritization with non-detailed data (Moilanen 2012), to enable well-informed land-use and conservation planning, systematic collection, maintenance, and the updating of biodiversity data should be a priority in all countries where possible, like in Finland.

Biodiversity is a multifaceted concept with many levels and high dimensionality (Noss 1990). This directly translates into a need for diverse biodiversity data because different data sets have different utilities for planning and prioritization (Box 2). In **I**, for example, we measured urban biodiversity as a set of community attributes (richness, biomass, abundance, etc.) associated with urban habitat types (biotopes), which we considered more informative in the context of resilient and multifunctional urban green infrastructure than a focus on protected species would have been, for example. This study would not have been possible without existing data about urban biotopes in the metropolitan cities.

Data needs for informative spatial prioritization or land-use planning are not limited to biodiversity. Especially in cities, data would also be needed about the user preferences of different green areas to gain socio-ecologically informative prioritizations (Karimi et al. 2015; Korpilo et al. 2018). Accessibility to green areas (**II**) is an important factor of urban green infrastructure, and accessibility models should be expanded to other cities in Finland and the world. Having up-to-date data about the intensity of different land-uses is also important so that it can be linked into ecological condition of different areas (**III**).

Practically, if spatial prioritization is to be used to support land-use planning, all input data should be systematically collected from the entire planning area because spatial prioritization is very sensitive to spatial biases in data quality (Kujala et al. 2018b). For example, many data layers had to be excluded from the Uusimaa cases because they covered only individual municipalities (**III**). National or regional inventory campaigns would therefore best serve the purposes of regional planning because municipality-centered campaigns would likely result in data which is too heterogeneous. Nationally collected data would also allow analyses that exceed regional (or municipal) borders (**III**). However, it is worth noting that spatial prioritization does not have to be, and should not be, the only data source in ecologically aware planning but can be complemented with other, possibly localized, data sources. For example, if an inventory of patches of endangered habitat would be available from only one small sub-area, nothing should prevent land-use planners from including those habitat patches in the final land-use plan, along with top-priority areas from a systematic Zonation analysis.

As mentioned above, there was a good variety of biodiversity data available for my studies (**I**; **III–IV**). However, the data was originally scattered across many administrational sources and examining and collecting all the relevant data was indeed time-consuming, even when the data layers did exist prior to the start of this work. Especially in **III**, the administrative processes needed to gain access to some data layers were cumbersome and slow (up to months). In Finland, all biodiversity data should be collected under one platform that would allow its use in planning. Currently, there are initiatives working towards that goal: The Finnish Biodiversity Information Facility (FinBIF), under the Finnish Museum of Natural History, aims to collect all species data under an open access platform, and the Finnish Ecosystem Observatory (FEO) by the Finnish Environment Institute is a similar initiative for habitat distribution and condition data. These types of endeavors should be executed by strong and well-resourced institutions capable of coordinating biodiversity inventories on a national scale, so that ecologically aware land-use planning would not be hindered by a lack of adequate data. As demonstrated by the recent success story of biodiversity mapping by the Finnish Inventory Program for the Underwater Marine Environment (VELMU), it is completely possible to compile diverse, high-quality, detailed, accurate, and geographically comprehensive biodiversity information for a large area. Since the early 2000s, the entire Finnish coast has been inventoried in over 150,000 sample locations using standardized sampling methods and providing observational data about species and marine environments. This allows species distribution models for hundreds of marine species and accurate spatial prioritizations across Finnish marine waters (Virtanen et al. 2018). This effort should be repeated in the terrestrial areas as well.

Conclusions: Well-informed land-use planning relies on adequate and diverse biodiversity data. Hence, systematic inventories and species distribution modelling should be done throughout Finland. Inventories should span multiple higher taxa and cover many levels of biodiversity as well as current land-use and management practices to enable flexibility in planning. Especially in cities, systematic data about human values and use in different urban environments and green areas should also be collected and developed. Furthermore, access to standardized biodiversity data needs to be developed.

4.3. ECOLOGICAL CONNECTIVITY IS MORE THAN JUST LINES ON A MAP

As my work demonstrates, connectivity can be included in spatial prioritization in many ways (**I**; **III–IV**). We utilized commonly-used methods to include patch-level connectivity, the Matrix connectivity (Lehtomäki et al. 2009) in **I**, **III**, and **IV**, and distribution smoothing -type preprocessing of certain input layers in **III–IV** to increase ecological realism in the prioritization. In those types of analyses, the priority of some patches, such as high-quality habitats, is increased if there are other similar patches nearby, as high-quality aggregations of habitats are expected to maintain biodiversity better than single isolated patches. Furthermore, in **IV**, we demonstrate how spatial prioritization can be used to identify comparatively well-connected parts of the landscape at the network level as well as structural connections in the landscape. These methods should benefit operational land-use planning but they do imply some changes to how connectivity is currently treated in land-use planning.

Typically, landscape-level connectivity is accounted for by marking linear symbols for connections in-between certain ecologically important sites such as nature reserves, especially in land-use planning at the regional or whole-municipal levels (e.g. Helsinki City Plan 2016; Regional Council of Uusimaa 2019). These linear symbols should then convert to sufficient and continuous green areas in detailed zoning. Linear corridor symbols can be very long and traverse through varying landscapes and even across dispersal obstacles like roads, which, in reality, likely results in low gains for biodiversity (Mutanen and Mönkkönen 2003; Boitani et al. 2007; Gippoliti and Battisti 2017).

The goal for preserving connectivity and ecological networks should be to ensure maintenance of populations of all species at the landscape level rather than facilitating movement of some individual animal species. Therefore, connectivity conservation should be cognizant of the fact that habitat quality in the matrix greatly influences the maintenance of populations in the landscape (Boitani et al. 2007; Cai and Pettenella 2013; Reider et al. 2018). In **IV**, we abandoned the typical division of a landscape into core areas, connections, and the matrix. Instead, we used Zonation to identify large, contiguous structures that had generally comparatively high habitat quality (indicated by a high density of biodiversity features) and that were separated from each other by more degraded parts of the landscape. Generally, those large structures, i.e. ecological networks, should not be further fragmented.

Large aggregations of high-quality sites and the accompanying areas of relatively high habitat quality would be hard to preserve with traditional conservation measures. For example, it would be completely unrealistic that the entire large networks in **IV** would be preserved as protected areas. Land-use planners, however, would have more flexible options to define areas where certain, but not all, human actions should be restricted. Ideally, most valuable and sensitive top-priority sites would be protected as regular protected areas, and the human actions in the surrounding matrix, if needed, would be restricted with a suitable land-use zone (Hanski 2011; Kremen and Merenlender 2018). For instance, Uusimaa regional plans include the 'MLY' zones that are restricted to forestry use and forest protection. Similar zones with more detailed restrictions to harvesting, for example, could work in the surroundings of aggregations of top-priority sites such as in the Green belt of Helsinki. Corridors themselves should be limited to short landscape bottlenecks (e.g. across agricultural zones) which should be ensured or enhanced via restoration (**IV**).

Conclusions: Even though connectivity has been a topic for ecological research and land-use planning discussion for decades, the current land-use planning practices cannot sufficiently account for connectivity in a way that would hinder biodiversity loss. Instead of elongated linear corridors, the focus should be in maintaining large, contiguous, and ecologically high-quality structures in landscapes to ensure biodiversity in the long run. Land-use planning symbols, such as suitable zones, should be developed to meet this aim.

4.4. URBAN AREAS ARE UNIQUE IN TERMS OF BIODIVERSITY, PLANNING – AND PRIORITIZATION

All my works included a growing metropolitan area, either from the perspective of the metropole itself (**I**, **II**) or in a regional context (**III**, **IV**). I dare to argue that, due to heavy economic and land-use pressures, the high prevalence of social aspects, and unique characteristics of biodiversity, urban areas create a unique context for spatial prioritization compared to conservation planning of rural areas.

A growing population, miscellaneous land-use pressures, and high land cost within a growing city introduce great challenges to urban conservation and green infrastructure planning (Bekessy and Gordon 2007; Dorning et al. 2015;

Haaland and van den Bosch 2015). Decisions to limit development in some places can lead to land-use trajectories that can (due to e.g. different path-dependencies) be hard to modify later (Salo and Mäntysalo 2017). Reduced development in inner-city areas, for instance, can lead to urban sprawl with its own associated environmental problems (Dupras et al. 2016; Koprowska et al. 2020), as appears to have happened in the Helsinki region as well (Laakso 2012). Therefore, if spatial prioritization in growing cities is to affect land-use planning, objectives must be very carefully set; inappropriate objectives can result in neglect and loss of areas that would have been important based on more appropriate objectives (Box 2). In **I**, for example, the goal was to identify priority areas in terms of diverse and resilient ecological communities that were likely to facilitate diverse ecosystem functioning. These communities were identified according to the Biodiversity Quality concept (Feest 2006; Feest et al. 2010). This goal is arguably better aligned with the paradigm of multifunctional green infrastructure that supports multiple ecosystem processes, compared to, for example, preservation of urban populations of individual endangered species (Shwartz et al. 2014). The goal in **II**, on the other hand, was to identify the most important green areas in terms of social equitability of access, a very important element in the planning of socially sustainable cities (Wolch et al. 2014; Kimpton 2017).

Urban spatial prioritizations should indeed address both social and ecological aspects of urban green infrastructure (Pickett et al. 2016; Hansen et al. 2019; Jerome et al. 2019). My works, for example, allow the examination of priority areas from the perspective of urban biodiversity (**I**) and human accessibility to nearby green areas (**II**). As can be seen in Figure 5, these different aspects of local green infrastructure partly conflict with each other as the urban fringe would be of high value for biodiversity but holds only limited potential for the everyday recreation of local people. Spatial prioritization could well balance between

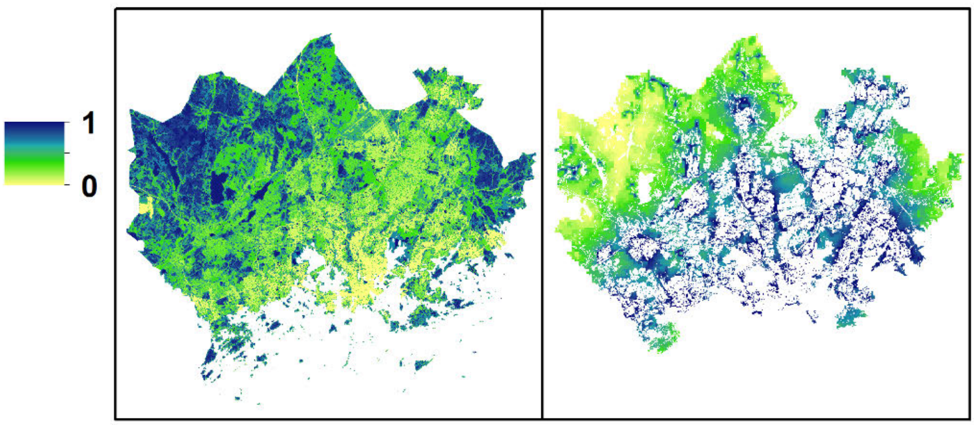


Figure 5 Comparison of the spatial prioritizations of urban green areas based on urban biodiversity (**I**) on the left and human accessibility (**II**) on the right. The analyses describe the value of green spaces from two very different perspectives and with somewhat different priority patterns.

these two types of datasets, and many others including, for example, provision and demand of ecosystem services (Cimon-Morin and Poulin 2018) or user activity and appreciation of urban parks (Heikinheimo et al. 2020). However, also doing the prioritizations separately for different purposes allows in-depth assessment and comparison of the importance of different sites for different perspectives of the green infrastructure. Furthermore, when combining very different objectives in prioritization, the general and technical objectives, such as selection and preprocessing of input data, must be very carefully considered with many stakeholder groups and professionals of different disciplines (Honeck et al. 2020).

Urban biodiversity differs from its rural counterpart, making cities worth including in conservation prioritizations (Niemelä 1999b; Kowarik 2011; Soanes et al. 2018). However, because data availability is usually higher in cities than in the countryside (Ward 2014) and because spatial prioritizations are sensitive to spatial biases (Kujala et al. 2018a), many urban biodiversity datasets would likely need to be discarded from prioritizations at larger geographical scales, resulting in a possible neglect towards urban biodiversity. This was the case, for example, in the Helsinki Metropolitan area. In **III**, a lot of inventory data from the Helsinki Metropolitan area was left out from the regional analyses because the data was only available for the metropolitan cities. On the other hand, in **I**, we identified some top-priority urban ecosystem sites, such as botanical gardens or old military fortifications, that were not prominent in the regional analyses (Fig. 6a). This example highlights the benefits of separate spatial prioritizations for urban areas.

To assure cost-efficient conservation, it is good to examine the urban areas from regional or national perspectives as well. In **I**, we included a regional perspective to the assessment of urban species assemblages to increase emphasis on areas that support biodiversity most characteristic for local urban ecosystems, and which cannot be conserved elsewhere efficiently. On the other hand, high-priority areas in the Helsinki Metropolitan area identified in **I** and **III** generally coincide with limited exceptions (mentioned above), indicating that sites that are important for the local urban ecosystem are valuable also at a wider geographical scale (Fig. 6b). In fact, some urban forests in the Helsinki Metropolitan area appear to hold even more conservation importance from the regional perspective than a local one (Fig. 6b), which is very useful information for local urban planners and conservationists. However, the objectives of the large-scale prioritizations might not be fully adequate in cities, which should be remembered during interpretation. If it turns out that high priorities in some urban area are based on rare biodiversity features (at the regional scale) that can still be satisfactorily protected outside cities, it might not be cost-efficient to conserve that particular urban spot – unless the area is identified as important in the local socioecological context as well.

Conclusions: Conservation of biodiversity in an urban context is complicated by powerful land-use pressures and high land

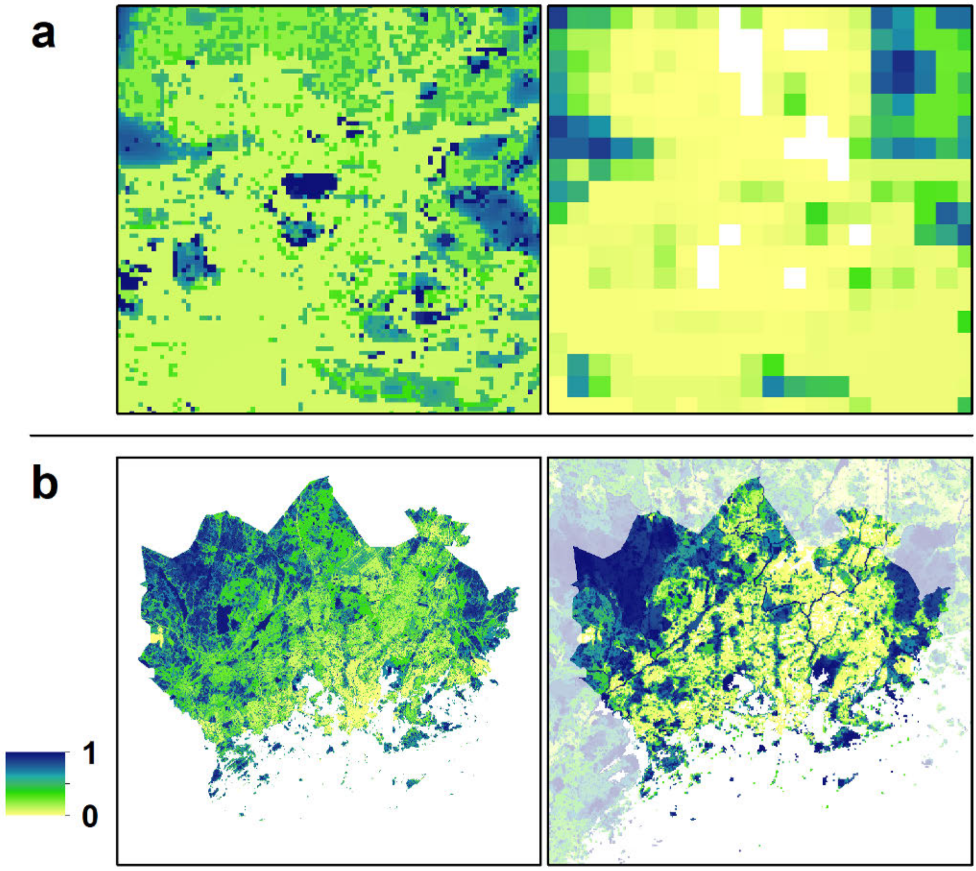


Figure 6 Comparison of the priority ranks in Helsinki Metropolitan area based on the analyses from the Metropolitan area only (**I**) on the left and the Uusimaa region (**III**) on the right. There are some dissimilarities between the two rankings (**a**). However, the general priority patterns are similar in both prioritizations, even though they are based on completely different aims, settings, and input data (**b**).

cost. This should also have implications on the way spatial prioritizations are done and interpreted. Urban areas differ from the rural areas based on their data availability, flora and fauna, and socioecological contexts, which emphasizes the need for separate spatial prioritizations for major cities. Due to the high demand for cost-efficient planning, as well as the multi-use nature of urban green infrastructure, including different ecological and social aspects, designing prioritization analyses, and formulating their objectives is an important but challenging task.

4.5. SPATIAL PRIORITIZATION CAN BE AN IMPORTANT PART OF THE LAND-USE PLANNING PROCESS

III was the first endeavor in Finland to provide a holistic understanding of the biodiversity values for regional zoning, covering all major habitat types as well as species, using spatial prioritization. The project was executed mainly as a collaboration between regional planners and university researchers with an additional expert panel representing different stakeholder groups. External consultants were also used in identifying and describing the Zonation top-priority areas (the 'LUO' areas, Section 3.3.2). Initially, regional planners adopted the top-priority sites in the regional plan somewhat directly. Even though the symbols were opposed by some stakeholder groups, and eventually voted off from the main zoning map by the regional politicians, regional planners (at least the ones I have talked with) even still consider Zonation analyses and subsequent results valuable and useful in their work. This is also indicated by the fact that the regional planners continued collaboration with Zonation experts after the first project (Jalkanen et al. 2018a, b), and that Zonation results have been later used as a criterion for identifying regionally important nature areas, for example (Manninen et al. 2019). The Uusimaa case thus serves as a good example of successful collaboration between researchers and implementers. However, operationalizing spatial prioritization in an existing planning framework requires understanding of what the role of prioritization could be.

In general, proper land-use planning decisions consist of both the planning outcome and the planning process. The outcome (e.g. a zoning plan) should serve its purposes efficiently. The legitimacy of the process, such as how the plan is prepared, requires, for example, that all relevant stakeholder groups are involved and are comfortable with the chosen planning approaches. Even if some stakeholders would eventually not be satisfied by the plan itself, they can still accept it if the procedure of reaching the plan was appropriate. Ideally, spatial prioritization could facilitate both good planning outcomes and processes. As demonstrated throughout this thesis, prioritization can be used to get planning outcomes that are justified from an ecological perspective (e.g. Section 4.1).

Spatial prioritization can facilitate collaborative and deliberative planning (Raymond et al. 2014; Beza 2016) in two ways. First, it can increase knowledge transfer and openness in the decision-making. Setting up a prioritization project, such as formulating objectives and designing analyses, in a collaborative effort forces people from different backgrounds and institutions to verbalize their values and appreciations in a systematic manner, which is already by itself important for open and democratic decision-making (Bekessy et al. 2012). The discussion needed in collaborative planning with spatial prioritization could also increase the overall relevance of ecological issues in land-use decision-making (Dewulf et al. 2020). This naturally requires that all the relevant stakeholders are involved in the process (Knight et al. 2006, 2011). In **III**, for example, one regional planner later concluded that engaging more municipal planners and regional politicians in the Zonation project could have enhanced its acceptance among different stakeholders. Because spatial prioritization may seem complicated at first, all the engaged stakeholders should first be taught its basics, so that the tool does not appear as 'a black box'.

Second, spatial prioritization can work as a practical platform for deliberative valuation of biodiversity in different planning situations (Raymond et al. 2014). It could be used as a 'boundary object' (Star 2010; Abson et al. 2014; Schröter et al. 2014), something that is specific enough to keep discussion on topic but still vague enough to leave space for personal or institutional values, interpretations, and integrity, and that enables decisions and implementation among different, even opposing, stakeholders and institutions. A municipal planner, for example, can look at the priority map from a very different perspective than a regional planner but it can still help them to reach a more shared land-use vision. As one spatial prioritization expert, quoted by Sinclair et al. (2018) in their paper excellently put it: "Prioritization is not an exact science, but a dialogue that software tools can effectively mediate."

Spatial prioritization is not an attempt to remove political or subjective decisions and values. On the contrary, formulating objectives, considering, for example, the weighting system, or interpreting the results inherently contains subjective and value-laden decisions. Instead, spatial prioritization offers the possibility to articulate those values openly and to follow them systematically and thus, bring transparency to spatial decision-making (Bekessy et al. 2012). Zonation results should therefore not be portrayed as objective "truths" in an attempt to depoliticize land-use planning and conservation questions (Paloniemi and Rekola 2019), but the assumptions and decisions that are inherent in the analyses should be discussed openly.

Conclusions: Operationalizing and mainstreaming spatial prioritization, as well as realizing most of its potential, requires that it be carefully embedded in wider land-use planning processes. Spatial prioritization is not planning by itself, but a facilitator of good land-use planning decisions and discussion. From a planning perspective, going through the process of spatial prioritization, including all the debate and decisions that are needed in designing and interpreting analyses, can be as valuable as the actual prioritization or zoning plan outcome itself. Embedding spatial prioritization in land-use planning process can increase collaborative and deliberative decision-making. This, however, requires that stakeholder engagement be done appropriately and that the decisions are truly shared openly. Otherwise, there is a danger that spatial prioritization would be used as a quasi-objective 'black box', providing arguments for land-use planning decisions in a non-transparent way.

4.6. SPATIAL PRIORITIZATION FOR SYSTEMATIC, TRANSPARENT, AND ECOLOGICALLY SUSTAINABLE LAND-USE PLANNING

In my thesis, I have discussed how spatial prioritizations should be designed to be informative for urban and regional planners, and what kinds of implications the context of land-use planning brings for spatial prioritization. In addition, as a general conclusion from my entire Doctoral work, I wish to elaborate on how spatial prioritization could advance ecological values and biodiversity to be more systematically accounted for in land-use planning.

Land-use planning is an active balancing of conflicting spatial interests, which typically happens through negotiations between planners and sectoral experts, and/or stakeholders (Albrechts 2004, 2012; Mäntysalo et al. 2011; Paloniemi and Rekola 2019). It is evident that this protocol is not sufficient if the biodiversity crisis is to be tackled (Newbold et al. 2016). Stronger emphasis on biodiversity in land-use planning has been called for in agreements and proposals at the global level (IBPES 2019c), EU (EU Science for Environment Policy 2016; EU Biodiversity Strategy for 2030), and Finnish-state level (Auvinen et al. 2020). Proposals such as 'no net land take' (EU Science for Environment Policy 2016) or 'no net loss of biodiversity' (Auvinen et al. 2020) imply that, in the future, land-use planners may need to be prepared to preserve biodiversity and (socio)ecological values much more effectively than currently while balancing different land-use interests. Spatial prioritization could offer a systematic and transparent approach for choosing areas for protection as well as for development (Bekessy et al. 2012). As illustrated in Figure 7 (that builds upon the process of spatial prioritization; Box 2), spatial prioritization outcomes could be iteratively compared and balanced between other land-use needs. Preserving high-priority biodiversity areas could conflict with, say, the most suitable areas for urban development at certain locations. Then, post-processing analyses such as Landscape Identification (Sections 1.3.2.2, 3.3.2) could be used to estimate the irreplaceability for biodiversity in overlapping areas, or new prioritizations could be done excluding those conflict areas to see what priority patterns would emerge in the new land-use scenario (also taking into account other simultaneous land-use pressures such as forestry). This information could then be used to decide which land-use type (e.g. urban growth or conservation) should be preferred, how the negative ecological impacts would be compensated, or which kinds of mitigating policies should be included in the guidelines of the plans.

As I touch upon in **IV**, sustainable land-use cannot really be achieved with only one land-use strategy. The primary application of spatial prioritization has been identifying candidate sites for protected areas (McIntosh et al. 2017). Another common application of the approach has been the identification of areas for ecological restoration (Moilanen et al. 2011b). While they are among the cornerstones of conservation biology, it is evident that protected areas or restoration alone cannot halt biodiversity loss, because a great majority of land is occupied for commercial or other uses (Maron et al. 2012; Visconti et al. 2019). In addition to protection, some areas are needed for land sharing (Kremen 2015); simultaneously supporting human wellbeing and recreational use of nature areas or allowing economic use of natural resources, yet safeguarding local biodiversity values by adopting appropriate management practices (Opdam et al. 2006; Hanski 2011; Cai and Pettenella 2013; Kremen and Merenlender 2018; Reider et al. 2018; Hansen et al. 2019). Furthermore, it is quite obvious that not all ecologically harmful anthropogenic actions could be excluded in land-use planning. Instead, those actions should be placed such that their negative impacts have been minimized (Kareksela et al. 2013; Moilanen 2013; **I**). Spatial prioritization could therefore be used to identify areas for (at least) three, mutually complementary, types of land-uses (Fig. 7):

i. Protected areas. This category would include areas with the highest ecological priorities. They would be managed primarily for conservation purposes as done currently.
ii. Areas for land sharing. These areas could serve as multifunctional areas in which human activities would be allowed, but biodiversity would also be ensured (Schneiders et al. 2012). Identifying these areas could be based on, for example, large ecological networks in **IV**, and they would be managed as providing socioecological values themselves and as the matrix that supports more strictly preserved areas. These types of landscapes follow the ideas of 'conservation landscapes' (Hanski 2011), 'working lands conservation' (Kremen and Merenlender 2018), or ecological networks in human-modified landscapes (Opdam et al. 2006). Coordinating the management of these areas would require many types of land-use regulations.
iii. Areas for intensive anthropogenic utilization. Spatial prioritization outputs could be used to identify areas where conservation could be excluded and other land-uses allowed without conservation-related restrictions. Generally, these areas should be placed following the principle of ecological impact avoidance (Kareksela et al. 2013); in other words, located in areas where the expected ecological impacts would be low. With this method, for example urban zones could be identified where general-level planning could be very loose regarding ecological issues. Additionally, some ecological features such as rare species would not necessarily be accounted for in the urban development, if those features could be sufficiently preserved in protected or land sharing areas. All types of endeavors that support biodiversity would of course be highly supported in these areas of intensive utilization as well (e.g. greening or ecological design in the urban zones; Hansen et al. 2019), but they would not need to be systematically coordinated.

In addition to the abovementioned land-use types, spatial prioritization could be used to identify areas for restoration (Moilanen et al. 2011b; **IV**), or ecological compensation (Moilanen et al. 2020), which could be used to mitigate the ecological losses that would take place in the areas of intensive anthropogenic utilization.

The workflow described in Figure 7 would require simultaneous inclusion of conservation, urban, and traffic planning, but also mining, forestry, agriculture, and other types of extraction, or use of natural resources into the same analysis of optional land-uses. In addition, the model requires extensive stakeholder engagement in many steps of the process (Section 4.5). Naturally, this approach would necessitate routinely-collected, comprehensive, and high-quality data about biodiversity and socioecological features (Sections 4.2, 4.4). This type of approach could be used at, for example, the regional scale, and possibly complemented with separate urban analyses (Section 4.4). The approach presented here would require effort in the land-use planning process, but it would allow ecological values to be accounted for systematically, effectively, and transparently. This would also help planning to meet the recent ambitious goals for sustainable land-use.

Conclusions: Spatial prioritization could be used for much more than just for identifying best candidate sites for conservation. It could be a tool for optimization between many land-use needs flexibly and for achieving no-net-loss of biodiversity by using three mutually complementary strategies: conservation, land sharing, and intensive anthropogenic utilization (ecological impact avoidance, possibly coupled with ecological compensation). Admittedly, this framework would be rather ambitious given the social, political, economic, and legislative reality we live in. However, advancing in small steps and applying best practices learned along the way, land-use planning could be made more systematic and ecologically informed, possibly with the help of spatial prioritization.

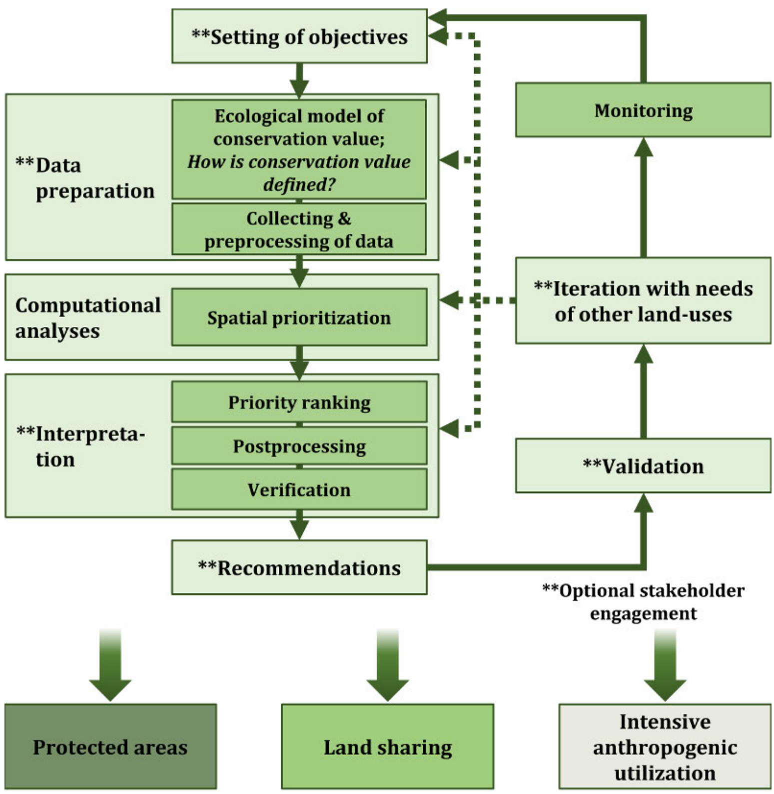


Figure 7 A framework for using spatial prioritization for collaborative and systematic land-use planning process. With iterative comparison and balancing with other land-use interests, spatial prioritization can be used to identify areas for conservation, land sharing, and intensive anthropogenic utilization (ecological impact avoidance). These could be complemented with analyses for ecological restoration and compensation. Stakeholders and land-use planners would be engaged in setting up the prioritization project and in interpreting the results to make the land-use planning system open and transparent. This framework would facilitate ecologically sustainable land-use decisions.

4.7. THE WORLD IS NOT READY YET – PROSPECTS FOR FUTURE RESEARCH

Spatial prioritization is a flexible tool that has proven to be of utility in many types of planning cases. However, further research and, most importantly, adequate data would be needed to increase the realism in prioritization analyses and their implementation.

A lot of biodiversity data is based on remote sensing products (e.g. **III**), and their accuracy and reliability should still be improved to allow more detailed spatial prioritizations (Lehtomäki et al. 2015). Furthermore, additional information is needed on how different land management types complement or support each other in terms of ecological communities and biodiversity conservation (Mazziotta et al. 2014), which would serve especially systematic identification of areas for land sharing (Fig. 7). More accurate connectivity requirements of urban species and populations would be important for fine-scale prioritization in fragmented urban areas (Bauer and Swallow 2013).

As cities are foremost habitats of people worldwide and developed for providing housing, transportation, services, and work for residents, the human perspective is crucial in spatial prioritization. In addition to the data about urban biodiversity, data about how people perceive, value, and use green spaces must be collected (Shwartz et al. 2014; Korpilo et al. 2018; Subiza-Pérez et al. 2019). Perceptions, uses, and valuations of green areas can vary between different seasons and socio-economic groups (Heikinheimo et al. 2017). It is important to analyze whether relationships between urban biodiversity and perceived biodiversity or recreational needs, for example, are complementary or in conflict (Botzat et al. 2016; Subiza-Pérez et al. 2019). Different digital user-generated methods provide a promising approach to achieve this information (Wang et al. 2019). Although the methods come with various limitations, they are rapidly developing (Heikinheimo et al. 2020).

The main limitation of spatial prioritization is the assumption of a static landscape, which naturally does not fully capture the complex relationships between land-use, use of natural resources, and conservation, or the effects of climate change to ecosystems. Although landscape dynamics can be partly accounted for in spatial prioritization by including different types of projections (e.g. species distributions in the future) as input data (Kujala et al. 2013), prioritization would greatly benefit from more integrative approaches to including different land change dynamics (Iwamura et al. 2018). Hopefully, in the future, more dynamic and complex spatial prioritization would be developed. This would be especially important when locating areas for land sharing between conservation and different forestry and agriculture actions so that analyses could optimize between several management options.

Another important topic I have not discussed in this thesis is climate change and how it affects the desirability of different land-use outcomes. Accounting for climate change complicates spatial prioritization (Kujala et al. 2013; Jones et al. 2016) and brings another dimension to the land-use debate (Dale et al.

2011). Furthermore, how climate change prevention and mitigation relate to conservation of biodiversity and urban socioecological values is a difficult scientific and political question (Rastandeh et al. 2018).

Finally, operationalizing and implementing spatial prioritization requires understanding of the social, political, institutional, economic, and legislative realms (Knight et al. 2011). Research can help to embed spatial prioritization in different planning contexts and cultures, and to choose the most appropriate forms of collaborative planning between prioritization experts, land-use planners, and other stakeholders (Reyers et al. 2010; Dewulf et al. 2020; Norström et al. 2020). This would be highly facilitated by active collection of the best practices, which in turn requires active, open, and standardized reporting of the design and success of different spatial prioritization cases, as called for by McIntosh et al. (2017).

5. CONCLUDING REMARKS

In my thesis, I have described how spatial prioritization in the context of operational land-use planning differs from conservation planning or academic research (Sections 4.1, 4.4, 4.6), how spatial prioritizations can be done for urban areas (Sections 4.2, 4.4), and how spatial prioritization could facilitate ecologically more sustainable land-use planning (Sections 4.1, 4.3, 4.4, 4.5, 4.6). Although my case studies have focused on the Helsinki Metropolitan area and the surrounding Uusimaa region, there is nothing case-specific in these prioritization analyses and similar analyses could be done anywhere else, conditional on the availability of suitable data. What is more case-specific in my studies is the general land-use planning system. Legal requirements for professional planning, as well as the public authorities' monopoly on land-use zoning, for example, are characteristic to Finland and they naturally greatly affect how applicable prioritization appears within local land-use planning processes.

As a practical matter, there is comparatively a lot of expertise in spatial prioritization in Finland. State-supported national prioritizations cover Finnish forests (Mikkonen et al. 2018), mires (Kareksela et al. 2019), and marine areas (Virtanen et al. 2018). My thesis contributes to this list by providing methods for prioritization in urban areas as well as more holistic prioritization covering all major habitat types. However, performing similar analyses in other cities or regions requires that adequate biodiversity and socioecological data becomes available. This would require a national inventory program and resourcing which was the case with the other abovementioned national-level prioritizations (Section 4.2). Naturally, the input data and outputs from the existing national prioritizations are already very useful for general land-use planning. Providing them in an easily accessible format and with appropriate instructions, like the LUO area description cards in **III**, would facilitate their use across regional councils and municipalities throughout Finland.

Currently, the Finnish Land Use and Building Act is under revision, and the new version is planned to come into force in 2021. The revised Act could promote the use of complementarity-driven and systematic approaches. For example, if city regions would become planned more as a whole in the future (as called for by e.g. the policy brief by the Finnish Environment Institute; Oinonen et al. 2019), spatial prioritization could be used to identify the most important 'backbone' of the green infrastructure for the city region, while the planning of the other areas would be left to the municipalities. Another pending matter is whether the demand for more strategic and less-detailed land-use planning becomes promoted by the new Act and how that would fit with the philosophy of accurate mapping and spatial explicitness in spatial prioritization. If regional and master plans become more strategic in the future, I still suggest that spatial prioritization provides useful supporting information for implementing said strategic plans. On the other hand, there is a growing demand for having biodiversity much more strongly emphasized in Finnish land-use planning, including also ecological features that are currently not legally protected (Auvinen et al. 2020), which would definitely call for efficient optimization tools such as spatial prioritization. Regardless of the level of detail in the future land-use plans, ecological information will also remain necessary in the future to achieve ecologically sustainable land-use, which is still demanded by the many international agreements Finland has committed to (e.g. CBD 2010; IPBES 2019c).

Finally, I repeat that I fully acknowledge I have written my thesis purely from a Zonation expert's point of view. There remains a plethora of questions in the planning and implementation perspectives that would need to be addressed if spatial prioritization would be really used in all the ways I have proposed, but one PhD project is not enough to answer them. The future will show how well systematic approaches and conservation planning tools become adopted in general land-use planning practices. Nevertheless, as demonstrated and discussed in this thesis, there are no technical or knowledge-related hindrances for making systematic, well-informed, and wise land-use decisions. The question is if we have the will, patience, and determination to put this knowledge into practice. Continuing with the example from J. R. R. Tolkien's stories, it is up to us whether we want to treat our Courts and Gardens like Saruman, the Wizard who left the path of wisdom, or like the High Men of Númenor. The choice is ours; we have the tools for both.

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This book is the story of a boy who loved nature and was thrilled with city plan illustrations. His quest for combining these two passions led him on a journey of many turns, from courses in urban ecology, conservation biology, and planning geography to his first Zonation analyses in a hut in the Finnish archipelago; to meetings with regional planners; to seminars abroad; late nights with new friends; to a job at a city planning department, even.

With adequate data, appropriate tools and analyses, and well-informed decisions about land-use, he realized, the world can be saved. One city, one region at a time.

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